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AEROASSIST

Key to Returning from Space and the Case for AFE

National Aeronautics and Space Administration

AEROASSIST KEY TO RETURNING FROM SPACE AND THE CASE FOR AFE

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PREFACE

Future expanded operations in space will require a new type of aeroassisted space transportation vehicle designed on the basis of fundamental data obtained by scientific experiments carried by a large test vehicle, the Aeroassist Flight Experiment described in this publication.

The civilian space program is at a challenging crossroad. We have the capability to develop technologies leading to new steps into space as exciting as was the exploration of the Moon. Within our grasp are long-lived Earth-orbiting laboratories, a permanent base on the Moon, and explorations of Mars with robots and with humans. Each of these steps offers the potential for tremendous scientific and technological breakthroughs that will be reflected in everyday life.

For example, repair and upgrading of expensive communications satellites in high Earth orbit (HEO) could become routine and be far cheaper than launching new units from Earth.

On the far side of the Moon an observatory would be shielded from interference generated on Earth and could consequently extend our astronomical penetration over a wide frequency spectrum into the far reaches of space. A spaceport on the Moon would also profit from the low lunar gravity to send greater payloads into space. Lunar materials offer potential for mining and manufacturing processes.

Exploration of Mars would shed new light on planetary geology and planetary evolution and would provide clues as to how life originates and evolves on a planet, clues which have been obliterated on Earth.

The NASA Civilian Space Technology Initiative (CSTI) and NASA's PATHFINDER program are dedicated to advancing ideas such as these and to identifying and developing their requisite technologies. An important thrust of these programs is to develop advanced, highly efficient, transportation systems for moving humans and materials to and from HEO and low Earth orbit (LEO), and to support missions to the Moon and to Mars. The Aeroassisted Space Transfer Vehicle (ASTV) is a key element for efficient transportation.

The ASTV gets its name from the fact that it uses aerodynamic forces, rather than rocket propulsion, to decelerate and maneuver, thereby achieving orbit modifications or entry into the atmosphere. Aeroassist can be used to move satellites efficiently from HEO to LEO, to decelerate into LEO when returning from the Moon or from Mars, and to perform an orbital capture at Mars. A properly designed ASTV results in much less mass having to be lifted into space for a given mission. The mass savings can result in a doubled payload capacity compared with that of an all-propulsive capture. This increased payload can translate into enormous benefits for the overall mission. For example, the mass required to be delivered to LEO for a piloted mission to Mars is reduced by almost half. Efficient aeroassist is recognized as being vital for the piloted mission to Mars.

At present, no validated aerobraking capability of this kind exists. Experience with Apollo and the Space Shuttle Orbiter has provided a very limited data base for the design of ASTVs. An efficient ASTV will require that a number of critical technologies be mastered. These include an accurate flow-field computational capability encompassing the chemical and radiative processes necessary to define the heating and aerodynamic environment. Advanced thermal protection systems must protect the payload from heating loads, and autonomous navigational systems must assure a safe aeropass and accurate insertion into the desired orbit.

Pioneering computational models have been developed to describe the environment of an ASTV during its aerobraking maneuver. Results derived from them form an important basis for the aerobraking concept. These models were developed using data from small ground-based experiments. The necessary simplifications and approximations incorporated into these models would require excessive conservatism if they were used as the basis for designing an ASTV. The high mass and cost leverage of aeroassist makes unnecessary conservatism in ASTV design very expensive.

To validate the computational models and develop the technology for efficient ASTV designs, NASA has initiated the Aeroassist Flight Experiment (AFE) as an element of CSTI. The AFE is a large-scale aerobrake experiment which will be deployed from a Space Shuttle Orbiter to fly through the Earth's upper atmosphere in 1995. It is designed to help provide the data base for all aerobraking applications using nonablating thermal protection systems. These applications include orbital capture at Mars, return from the Moon, and interorbital changes near Earth. AFE results will validate predictive and analytic methods and will provide a fundamental understanding of aeroheating mechanisms that will be valid for future high-energy entries into planetary atmospheres.

Thermal protection systems, guidance, navigation and control systems, and other technologies will be validated by the data produced in the AFE. Validation of these technologies is critical to the design and selection of future ASTV missions, and will directly influence the optimal choice of the aerobrake, and the size and general configuration of the vehicle.

While the computational models validated by the AFE will be useful in the design of a vehicle to enter the Martian atmosphere, a future AFE-type mission is required for the much higher entry speeds of a Mars mission returning to Earth.

The purpose of this publication is to discuss in more detail the physics of aeroassisted maneuvers, the implications of timely development of the technology, the necessity of the AFE mission, and the AFE mission itself.

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SECTION 1: RETURNING FROM SPACE—THE CASE FOR AEROASSIST (An Executive Summary)

The Aeroassist Flight Experiment (AFE) is important in the development of a substantial and cost-competitive space industry. It is a research program to develop the technology base needed to design a new class of advanced entry vehicles that will play a key role in establishing a mature U.S. space presence in the next century.

A dynamic and economical space program in the 21st century will include many operations involving the return of satellites, materials, and products from high Earth orbits (HEO), lunar bases, and planetary missions. The common and dominant characteristics of vehicles returning from such missions will be their very high speed as they approach the Earth. This high speed must be reduced substantially before the returning vehicle can be landed safely on Earth or placed in low Earth orbit (LEO), where the Space Shuttle operates now and the Space Station Freedom will operate in the future.

LEO is a strategic locale that will always play a critical role in any space program. Its location just beyond Earth's appreciable atmosphere can be reached from Earth with the lowest cost in energy, and it is the natural and convenient spaceport location. In the next century LEO will contain a broad complex of assembly, research, repair, and production facilities. Their effective and cost-competitive use will require a class of routine workhorse transportation vehicles whose importance might be overlooked at a time when dramatic space exploration is occurring. Yet it is these vehicles, the Aeroassisted Space Transfer Vehicles (ASTVs) that will provide the solid transportation base on which a productive space industry will grow.

The ASTVs will be assembled in orbit and will never return to the Earth's surface. They will be used to transfer people and material from high locations to LEO. They will reduce their high velocities in the region of LEO by flying into the outer reaches of the Earth's atmosphere where aerodynamic drag will slow them to the appropriate speed for LEO. They will then maneuver out of the atmosphere and into a desired orbit. The present consensus is that this is the only cost-effective method of reducing the speed of such vehicles to the required level. For example, the cost savings of using aerodynamic drag over using retrorockets in returning from geosynchronous Earth orbit (GEO) is about 33%. Even greater cost savings can be obtained in moving material from the Earth's surface to LEO for missions to the Moon and Mars.

The ASTVs will operate at very high altitudes where the atmosphere is exceptionally thin and the flight data needed for their safe and efficient design are not adequately known. Much critical scientific research must be done to build the technology base needed to make such a design. The research program discussed in this publication, the AFE, is specifically aimed at acquiring the knowledge for this technology base.

The Future Space Program

One of the accepted goals of the space activities of the United States is to expand human presence and activity in space from low orbits around Earth out into the Solar System.

In 1986 the National Commission on Space recommended a bold national plan for the people of the United States. "To lead the exploration and development of the space frontier, advancing science, technology, and enterprise, and building institutions and systems that make accessible vast new resources and support human settlements beyond Earth orbit, from the highlands of the Moon to the plains of Mars."

Human expansion beyond Earth is an undertaking of great importance to the future of our species for which preparations should begin today. As a next step into the Solar System, the United States with international partners is developing Space Station Freedom to provide facilities for a permanent presence in LEO. A permanent presence in LEO permits humans to start building in space as they have built on Earth in the past. Crews based at a space station can assemble in space the advanced spacecraft needed for missions to the Moon and Mars. As a result of this and other international space station programs, we will most likely witness early in the coming century the first humans landing on Mars and the first permanent research stations on the Moon with outposts there to develop lunar resources.

The United States and the Soviet Union, looking towards economic competition in the utilization of space, have each developed space transportation systems to move humans and materials to and from LEO. Other nations are also developing cost-competitive capabilities in the important region near Earth and aggressively laying the groundwork for their expansion into the Solar System.

Aeroassist

The next important stage of human expansion into the Solar System is to develop advanced transportation systems to move humans and cargo between GEO, where many important Earth support satellites are based, and LEO, and to provide capabilities for landing humans and cargo on the Moon and on Mars and returning them to LEO from such missions. Such vehicles must rely on aeroassist technology to be cost effective.

Aeroassist is a generic term employed when aerodynamic forces are used to assist a spacecraft to change direction or slow down while flying through a planet's atmosphere. Aeroassist allows spacecraft to be captured into an orbit around a planet or to be slowed sufficiently to change orbital parameters, e.g., from a highly elliptical orbit to a LEO or, in the extreme case, to a planetary landing, with a minimum or zero expenditure of rocket propellants. In fact, using atmospheric drag to slow space vehicles is regarded as one of the largest contributors to making both lunar and Mars missions affordable. Aeroassist reduces by 50% the amount of material that has to be carried to LEO from the Earth's surface for such missions.

Aeroassist Space Transfer Vehicle

Many case studies of future missions to the Moon and to Mars, especially manned missions, have concluded that these advanced transportation systems must use aeroassist to increase payloads and reduce rocket propellant requirements. Indeed, without aeroassist some of the missions are not practical with available technology. For example, a proposal to establish a manned lunar base early in the next century (Figure 1-1) depends upon aeroassist at Earth for returning vehicles. Also, a key feature of NASA studies of manned missions to the satellites of Mars and to the Martian surface (Figure 1-2) is the use of aeroassist at both Mars and Earth.

A reusable ASTV is the next logical major requirement in space to complement the Space Station Freedom and the Space Shuttle and expendable booster space transportation systems now used to move personnel and materials from the Earth's surface to LEO and return. The ASTV will be used initially to move payloads among LEO, HEO, and GEO. For example, one early application would be to move expensive telecommunications satellites in GEO back to LEO for servicing or upgrading. From LEO such satellites could be returned to Earth via the Space Shuttle if for some reason they could not be serviced in orbit.

Recent estimates are that a fleet of up to 80 ASTVs will be required to meet projected national and international needs in the coming decades, and the first such vehicle will be needed in the first decade of the next century. The design of this new type of vehicle must be started soon if the United States is to have a competitive edge on the international markets that will be served by such vehicles.

When bringing cargo or personnel from the Moon or from HEO, an ASTV will enter the Earth's upper atmosphere at a velocity of almost 25,000 miles per hour. It will fly through the atmosphere (Figure 1-3) above 250,000 feet long enough for atmospheric drag to slow it by about 6000 miles per hour. Then it will maneuver back into space to rendezvous with a shuttle orbiter or a space station. The ASTV is a cost-effective approach because it will be capable of carrying up to twice the payload of a vehicle that relies entirely on rocket braking.

However, there are many technical questions about high-speed ASTV flights. These questions must be answered satisfactorily before an efficient ASTV design can be defined and vehicles can be developed for production in the quantities required. Otherwise the ASTV would have to be overdesigned for safety, with enormous penalties in the amount of usable payload that could be transported by each vehicle.

A preferred concept of an ASTV is a vehicle with a large, blunt, lightweight aerobrake. The practicality of the aerobrake depends upon our being able to predict accurately the aerodynamic characteristics of the vehicle and the heating effects on it at hypersonic velocities. The most important technical questions relate to understanding the basic aerothermodynamics affecting the flow of atmospheric gases around the maneuvering ASTV. Considerable progress has been made in establishing the basic principles through the use of small models in ground-based tests (wind tunnels, ballistic ranges, shock tubes, and plasma jets), and through applications of

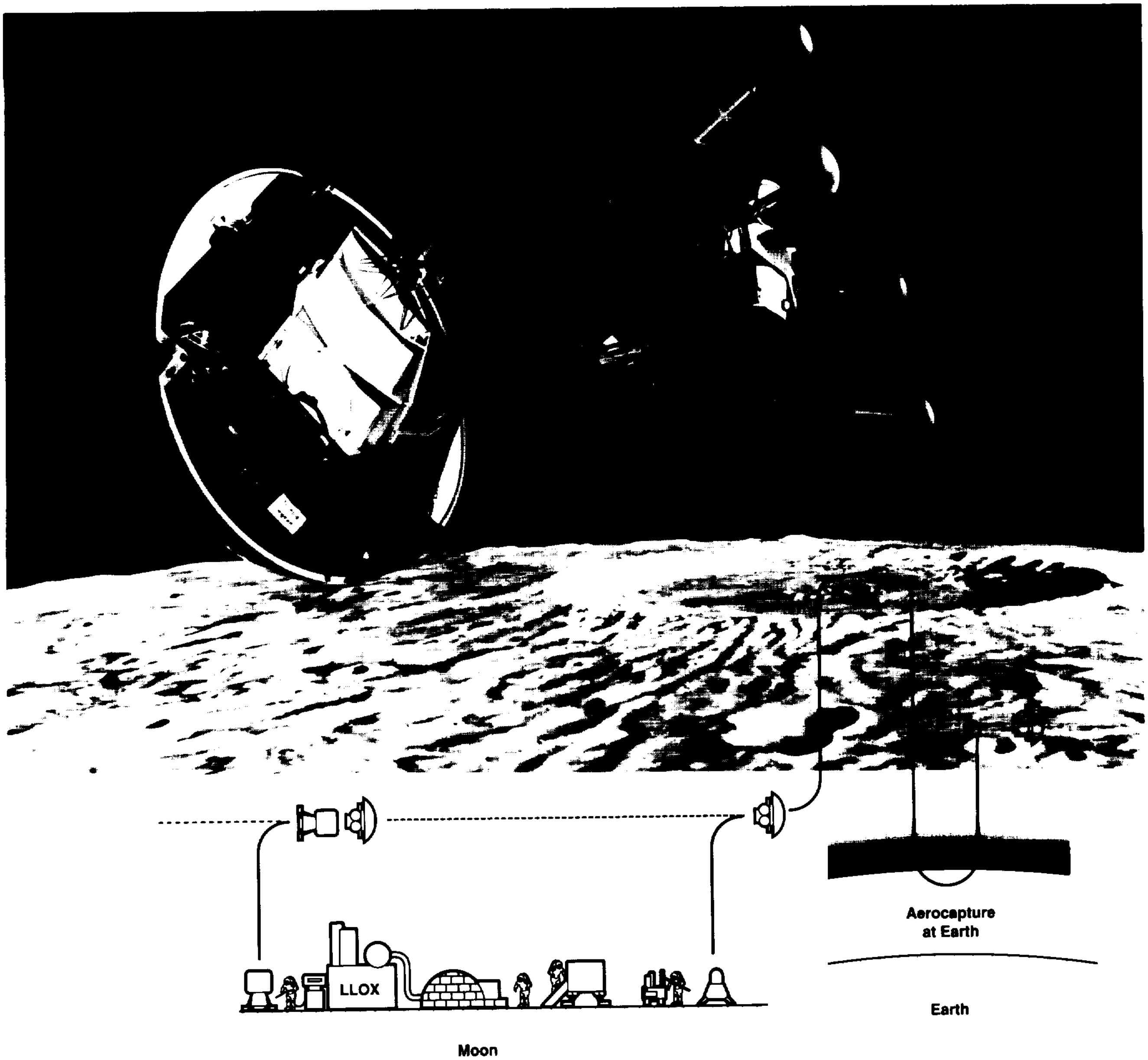

Figure 1-1. A permanent human presence on the Moon will depend on the use of aeroassist in Earth's atmosphere for return of personnel and materials to LEO.

computational fluid dynamics using supercomputers. However, flight test results are urgently needed over the range of hypersonic velocities that will be encountered by a spacecraft aerobraking from GEO to LEO to refine and validate the analytical methods to be used for design of the ASTV.

As an example, consider the aerobraking of a spacecraft returning to LEO from a deep space mission or from a high orbital mission such as from GEO. The maneuver will be at high altitude and at hypersonic speed. Under these circumstances the gas flow in front of the vehicle will be in a nonequilibrium condition; that is, an important part of the flow near the surface of the aerobrake will contain gas that is extremely hot (up to 45,000 K), and chemical reactions which would normally occur to cool the gas will not have time to proceed far toward completion because of the low densities. This nonequilibrated gas will radiate important amounts of heat to the aerobraking surface. For an ASTV returning from GEO, radiative heating to the forebody is nearly as large as convective heating.

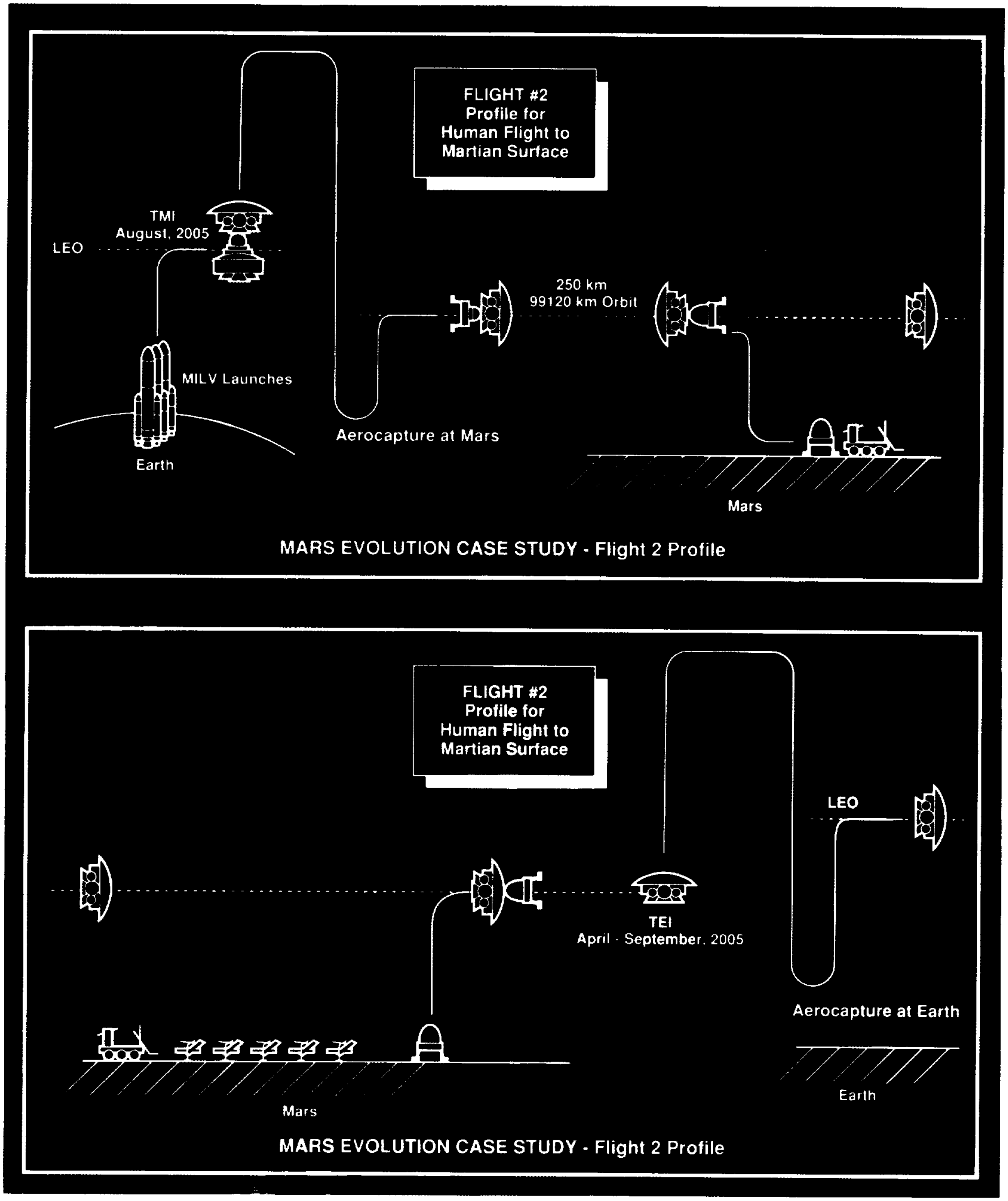

Figure 1-2. In several case studies for the establishment of human activities on the surface of Mars, considerable emphasis has been placed on the use of aeroassist at Mars and for return to LEO.

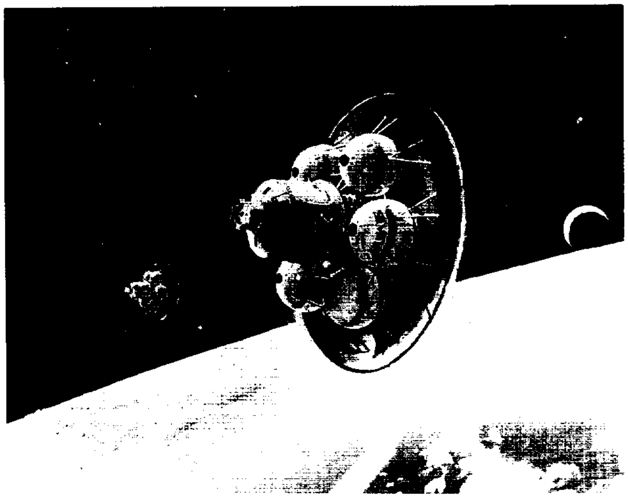

Figure 1-3. A concept for an ASTV employs a blunt aeroshell for atmospheric braking.

The heating is increased even further because of chemical reactions occurring on the wall of the spacecraft as a result of catalysis by the materials of the wall. This heating can increase the convective heating by about 40%.

Obviously there is a direct trade between thermal protection mass and payload mass. For spacecraft engineers to design an efficient and safe ASTV, the chemically reacting flow field and the resulting heating processes, and the material response of the thermal protection system (TPS) must be understood in detail. Preliminary computational models for these flow fields are being developed, but they currently use simplifications and approximations because of lack of basic science data. This is especially true in calculations of the amount of radiative heating. The problem is not only lack of physical data but also the complexity of the calculations relative to the capabilities of current computers. An ASTV designed with unvalidated analysis methods would of necessity include large safety factors and would thereby dilute or negate the advantage of aeroassist. The approximations and simplifications must be reduced and computational outputs must be verified by large-scale flight tests before the full potential of an ASTV can be realized. In addition, there are unpredictable variations of air density at the maneuvering altitudes so that guidance and control problems must be solved.

The AFE Program

The National Aeronautics and Space Administration has initiated the AFE to resolve these vital issues. The AFE is a subscale vehicle of a size sufficient to validate scaling rules while fitting within the payload bay of the Space Shuttle Orbiter. It will be launched from an Orbiter and fly a representative aeroassist trajectory through Earth's high atmosphere during which it will gather detailed measurements of aerodynamic and aerothermodynamic phenomena. The AFE, a model of which is shown in Figure 1-4, will be recovered by the Orbiter for return to Earth and inspection after the flight to evaluate material and structural performance, and for possible reuse.

The AFE is designed to examine the requirements of efficient ASTV design for maneuvers that can use a non-ablating heat shield. These include orbital changes in the vicinity of Earth, e.g., GEO to LEO, return from the Moon to LEO, and orbital capture at Mars. The arrival at Earth from a planetary mission will be at much higher speeds and will require an ablating heat shield. What is learned from the AFE mission will need to be extended to include the effects of this kind of heat shield.

AFE Research Objectives

The proposed instrumentation for the AFE is extensive and involves a number of scientific disciplines to obtain data vital to the design of an efficient ASTV.

An important task is to determine radiative heating levels on the aerobrake, their spatial distribution, and the spectra of the radiation. New data are required to resolve different interpretations of available data and the spread in current prediction techniques which are major issues in the choice of a concept for an ASTV.

The performance of several advanced thermal protection materials, including their catalytic efficiencies, needs to be evaluated. Candidate materials offer potential for important mass savings if they can be demonstrated as usable in the ASTV environment. Also, since a low catalytic activity of the wall material of the aerobrake can result in a substantially lower heating rate than that of a highly catalytic surface, quantifying these effects is important to the design of an ASTV.

Aerodynamic performance characteristics of the vehicle are most important. Flying an aerobrake in the rarefied upper atmosphere requires an understanding of the effects of unpredictable irregularities in atmospheric density that are known to be present at high altitudes.

The flow around the base of the vehicle, behind the front heat shield, including heating effects from the wake

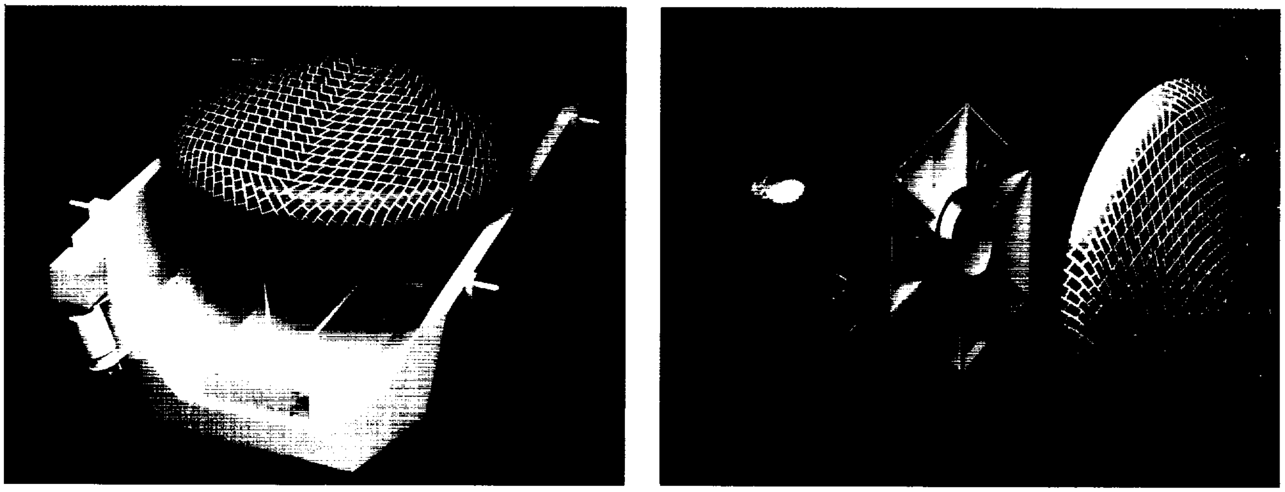

Figure 1-4. The AFE spacecraft and its experiments, a model of which is shown here, is designed to find answers to questions which must be solved to design an efficient ASTV system.

region, must be quantified. This is necessary to verify prediction techniques for the nonequilibrium base flow and wake region of a vehicle flying at high speed at high altitudes to determine the thermal and pressure loads needed for an efficient ASTV design.

Convective heating and pressure distribution on the aerobrake and characteristics of the plasmas generated in the flow field, including the concentrations of electrons, need to be measured.

Flight data must be provided to verify computational flow-field models which are needed to predict the performance and heating environment of future ASTVs and related vehicles.

Concurrent with and assisting the maturation of the AFE, a theoretical and experimental effort has been initiated to develop and validate computer codes to analyze the characteristics of ASTV flight. The AFE experiments will provide the critical flight data necessary to complete the validation of these modern computational codes which will be used to design a highly efficient ASTV capable of meeting the national need for high orbit (GEO to LEO) and cislunar (LEO to GEO to the lunar surface) space transportation systems.

Economics

The ASTV capability is needed for us to be competitive in forthcoming commercial space activities, as well as to keep our national position as a leader in Solar System exploration. The relatively inexpensive AFE mission will put the United States years ahead of a program that would incorporate a conservatively designed and instrumented operational ASTV which could provide the data to validate computer models. These early results are important to ensure that the first ASTVs will be efficient and competitive, and that the scientific basis will be available to continue development of our planetary programs. It is important to note that only a small amount of improved efficiency in an operational ASTV would make the early implementation of AFE a very economical and cost-effective program, even when applied over an initial small number of full-scale ASTVs.

Subsequent sections of this publication provide more details of the aeroassist concept and the rationale for its development. The immediate need for the AFE program is discussed. The flight mission and the vehicle and its instrumentation are described. Expected results are reviewed together with the future potential that can be realized to meet long-term national and international goals of expanding human activities into the Solar System.

SECTION 2: EVOLUTION OF THE AEROASSIST CONCEPT

In connection with the AFE program detailed in this booklet, aeroassist is defined as a generic term encompassing various maneuvers, including slowing, in which a vehicle enters the atmosphere, maneuvers using lift and drag forces, and exits without making a complete entry. The aeroassist technique in the present context involves the use of a large, saucer-shaped structure, the aerobrake, behind which is the main body of the spacecraft and its payload. The aerobrake also protects the cargo from aerodynamic heating. Large vehicles of this type will most likely be assembled in orbit. When, during an aeroassist mission, a planet's atmosphere is reached, the spacecraft uses the resistance generated by the planetary atmosphere on the aerobrake to slow the vehicle and maneuver it into orbit. Little propellant is expended during such a maneuver other than that required to control the attitude of the aerobraking vehicle relative to its flight path.

Aerobraking is important for spacecraft arriving at other planets, returning from the Moon to Earth, and transferring from HEOs (e.g., GEO), to the much lower orbits of Space Station Freedom and the Space Shuttle Orbiter. Various space missions (Figure 2-1) will require return to Earth at hypersonic speeds of 36,500 to 39,000 feet per second.

The potential benefits of aeroassisted velocity changes for orbital transfer have been recognized and studied since the beginning of the space age. For example, a study has shown that the amount of mass that must be lifted from the Earth's surface for a human mission to Mars can be nearly halved (Figure 2-2) if an aerobrake is used for atmospheric entry and landing on Mars and for later return to Earth orbit.

The ASTV flight regime involves higher velocities than the Space Shuttle and, in the region of significant aerodynamic heating, higher altitudes than the returning Apollo capsule. Although this high-altitude, high-speed flight regime is not unique to an ASTV, the flight of an ASTV will be entirely at high altitudes and thus in a region of low density. This is considerably different from the Apollo and Space Shuttle trajectories (Figure 2-3) which took these spacecraft rapidly through this

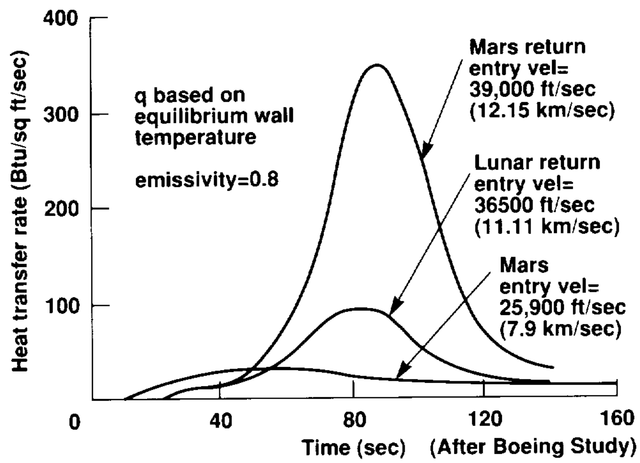

Figure 2-1. The range of velocities that will have to be encountered for aeroassisted vehicles in several space missions is shown, together with heat-transfer rates and the periods involved.

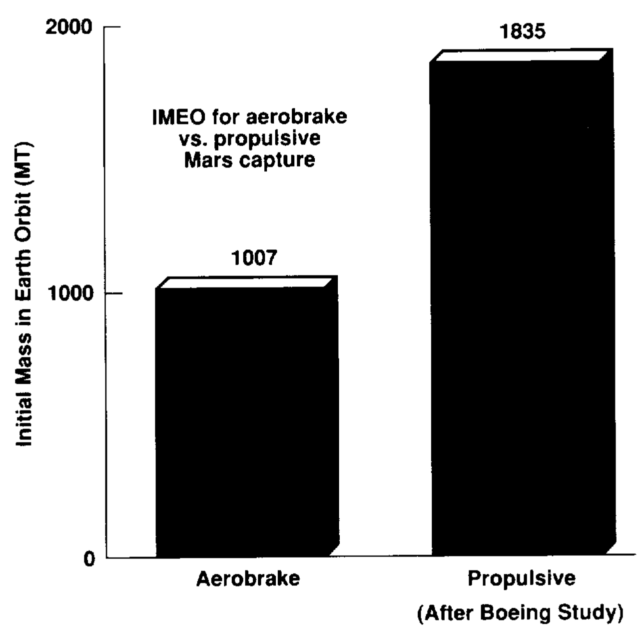

Figure 2-2. If aeroassist is used for human missions to Mars, the amount of material that has to be carried from the Earth's surface into LEO is almost halved.

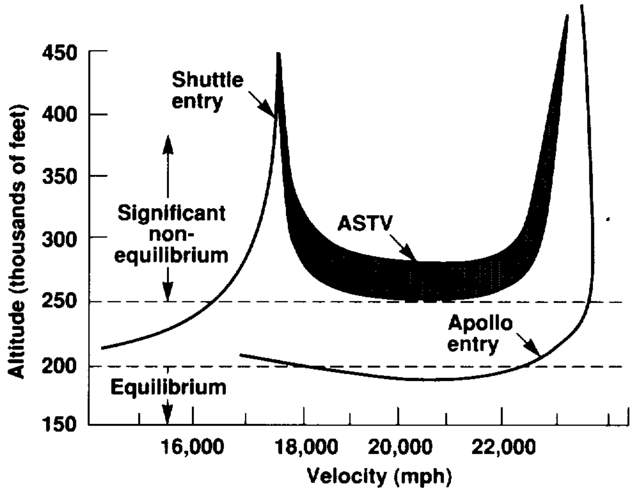

Figure 2-3. An ASTV using Earth's atmosphere must operate in a different regime from Apollo or the Space Shuttle Orbiter. As shown, the ASTV must operate at high velocities in the low-density upper atmosphere.

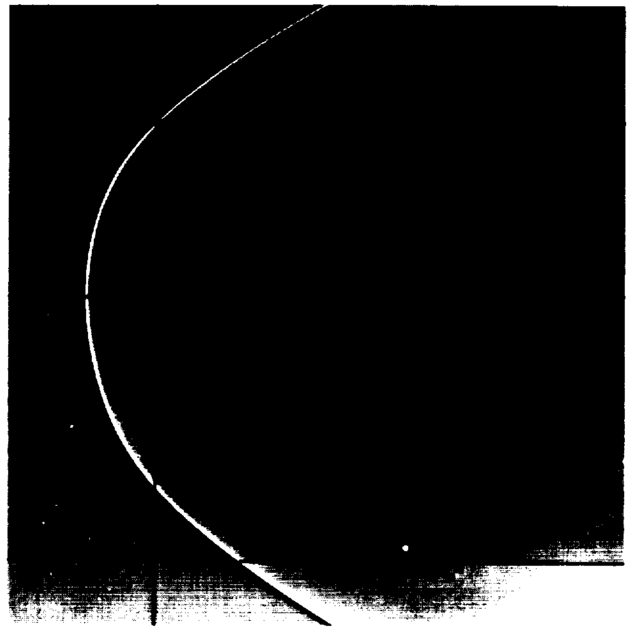

Figure 2-4. A detached bow shock is shown ahead of a blunt body at hypersonic velocity in a NASA ballistic range. Behind the shock the atmospheric gases are heated to high temperature and are in a nonequilibrium state.

atmospheric region for a landing on the Earth's surface and thus had other design criteria. By contrast, the ASTV will maneuver for several minutes at about 250,000 feet.

ASTV Flow Field

For efficient ASTV design a detailed understanding of the heating processes is required. The flow environment on a large ASTV is in nonequilibrium and results from interactions of many dynamic processes, which have a wide range of times to achieve a steady condition.

A spacecraft returning from a deep space mission or from GEO must perform aerobraking maneuvers at hypersonic speeds where a shock wave forms in front of the vehicle as shown in Figure 2-4. As the shock wave passes through the atmosphere in front of the vehicle, the gas is abruptly compressed and heated to the condition of the shock layer. As a result, the gas in the most forward region of a maneuvering ASTV becomes extremely hot, up to 45,000 K, and presents a difficult technical challenge of protecting the vehicle. These high temperatures would normally cause energy-absorbing chemical changes in the atmospheric gas, which would cool it. But the high altitude (with its resulting low air density) at which the ASTV flies results in relatively infrequent collisions between gas molecules. This lengthens the time to complete the chemical changes. They are only partially completed during the time the gas resides over a specific region of the forebody of an ASTV. A shock layer with a substantial portion nonequilibrated is termed a nonequilibrium shock layer. The result of the lack of chemical equilibrium is that the energy which would be absorbed in the chemical reactions remains in the form of high gas temperature.

The high-temperature nonequilibrium gases radiate strongly, so that the radiative heating from the ASTV shock region will be about equal to the convective heating.

Nitrogen and oxygen molecules dissociate into their respective atoms, and other molecular species are formed. As the gas proceeds along streamlines around the vehicle, more gas collisions cause the gas to begin to equilibrate its chemical states. Some species ionize,and the temperature relaxes from the nonequilibrium value of 45,000 K to about 8000 K. This large temperature difference underscores the importance of chemical reactions in understanding the mechanics of energy transport in the shock layer of a maneuvering ASTV. During an ASTV maneuver some of the atoms from dissociated air molecules will diffuse to the wall of the spacecraft and catalytically recombine there to reform the parent molecules (Figure 2-5). These reactions can release additional heat directly to the wall. The catalytic effect of wall materials

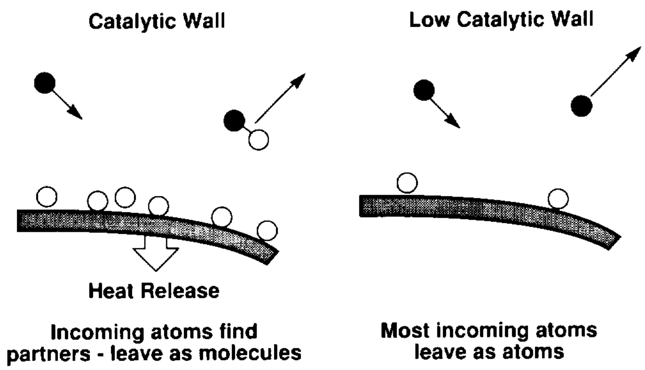

Figure 2-5. Materials of the aerobrake's wall surface can trigger reactions with the hot gases. Low catalytic materials can reduce the effects.

on such heat-releasing reactions must also be thoroughly understood since this source of heat can account for as much as 40% of the convective heating.

NASA first encountered the problem of nonequilibrium radiation during the Apollo program. A great deal of ground-based experimentation was conducted before the launch of the first Apollo vehicle to determine the extent of radiative heating of the vehicle in the environment of high-speed entry into the Earth's atmosphere. When the results of the experiments were extrapolated to the flight conditions, a large amount of radiation was predicted. Later, in 1967, one-quarter-scale models of the Apollo vehicle, named Project Fire, were flown with radiometric instruments to verify the predictions. The flight experiment resulted in radiative heating rates much smaller than those predicted from the ground-based experiments. Since the heat shield for the Apollo Command Module was designed from the ground-based data, the process led to a substantial overdesign of the module, which reflected through the Apollo vehicle, and such overdesigning of the heat shield will lead to a heat shield that is too heavy, which would negate the advantage of aerobraking. It must be added here that, even today, there is no unique theory that alone can explain the data from Project FIRE: several different theories explain the data equally well.

In addition, conditions in the wake region must also be understood. The present understanding of this region is that it also is not in chemical equilibrium (Figure 2-6). The heating to the rear of the vehicle would not be as high as to the front, but it would be too high to expose a payload to without any protection. Unfortunately, very significant uncertainties exist in predicting these nonequilibrium processes associated with using aeroassist.

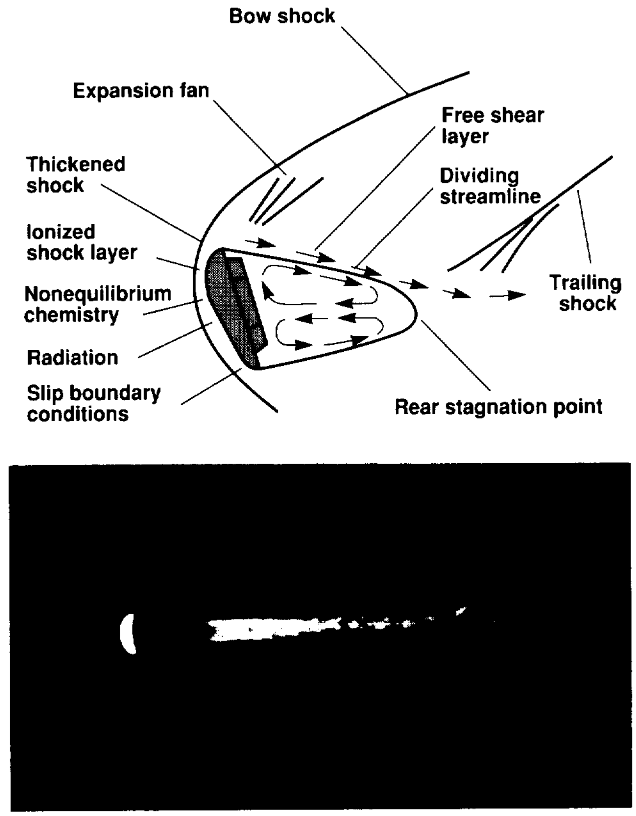

Figure 2-6. In the wake region, gas species recombine and produce radiation that could damage a payload behind the aerobrake. The photograph shows the complicated wake region of a model in a ballistic range.

Thermal Protection

As mentioned earlier, compared with the relatively quick entries of Apollo and the Space Shuttle Orbiter, the aeroassist vehicle uses a much longer period of aerobraking above 250,000 feet. The intentions are, indeed, quite different. While the Orbiter and the manned capsules use aerobraking to penetrate into the lower and denser atmosphere and to reach the surface of the Earth relatively quickly, the aeroassist vehicle uses aerobraking in the rarefied upper atmosphere to enter into an orbit around Earth. Thus the aerobraking regimes are quite different in the dissipation of the kinetic energy and consequently how the TPSs have to be designed.

The excess kinetic energy of the entering vehicle which it has to dissipate to be captured into LEO has to be converted into heat, chemical energy, or radiation. An ideal would be for the gas to carry off or to radiate the energy without depositing it onto the vehicle's surface. This ideal cannot be met because while much energy is carried away from the vehicle, some energy finds its way to the vehicle through radiative or convective heating, including catalytic reactions occurring on the surface. Accordingly, the aim is to minimize this unwanted energy flow and consequently to reduce the mass of material needed to protect the vehicle from excessive heating.

At the velocities to be experienced by an ASTV, thermal protection material may have to withstand a temperature of 1500 to 2000 K. Since current reusable thermal protection materials of the type used to protect the Space Shuttle Orbiter can withstand a temperature of up to 1800 K only, there is an urgent need to develop advanced materials for ASTVs. For example, a Mars sample return mission could use a high-drag aeroassist technique for landing on Mars, but would require a concurrent program to develop low-drag ablator aeroassist technology for capturing the returning, sample-carrying spacecraft into Earth orbit.

The three most practical types of heat shields are heat sink, ablative, and radiative. Heat sink thermal protection absorbs the heat in a large mass of material which never gets above a predetermined temperature. Heat sinks are generally very heavy and can lead to a fire hazard if they are not jettisoned before a spacecraft lands. At the beginning of the manned space program, ablative shields were most popular because they could be tailored for particular heating rates and total heat loads. However, they are efficient only at high heating rates. Early entry vehicles used materials that charred and ablated. Mercury, Gemini, and Apollo used an ablative material of sufficient thickness to protect the manned spacecraft during deceleration to a velocity at which a parachute system could be deployed for landing.

Later TPSs relied upon radiative protection. For example, the Space Shuttle Orbiter uses tiles of very low heat conductivity whose surface can reach a very high temperature without failing during the period of atmospheric deceleration. The hot surface radiates most of the heat away from the vehicle, and thereby reduces the amount of heat penetrating into its interior.

The ASTV will use radiative thermal protection since the accent in its design is reusability without having to return to the surface of the Earth. Moreover, the TPS for an ASTV must be highly reliable and require minimal servicing in space. Throwaway ablators are an easy solution for one-time missions, but clearly are not the way to go for an ASTV. However, a Mars return vehicle, which also would be expected to be retrofitted in LEO, might have to use ablators because of its high return velocity.

Computational Fluid Dynamics

Because of the deficiencies in ground test capability, the ASTV design must be based primarily on computational methods. Computational models are being developed for the ASTV flow fields. However, many approximations have to be used, especially in calculating the amount of radiation the surface will receive from the hot gases. These approximations are required because important physical data are lacking. The kinetic chemistry and the details of radiative phenomena are not fully understood. The consequence is that the present ability to predict the ASTV environment from small-scale tests in wind tunnels, ballistic ranges, arc-jet wind tunnels, and the like, must necessarily include large safety factors. A flight test is required to clearly define scaling factors from the small models used in ground-based tests to a full-scale ASTV.

The ASTV flow field presents a number of computational challenges which require significant advances over existing codes and procedures for predicting aerothermal loads and the responses of TPSs. Three-dimensional forebody and afterbody flows must be adequately resolved. Viscous terms must be included everywhere. Slip boundary conditions may have to be applied at the wall. An accurate model for wall catalytic efficiency is needed. Nonequilibrium flow must be computed reliably, and heat transfer due to radiation and convection within the TPS must be accurately modeled to minimize structural weight.

These computational techniques need to be developed. They will be reliable for system design and development, however, only if they have been verified by flight data. Such verification requires the use of a test vehicle with a representative blunt configuration capable of flying a realistic aerobraking trajectory in the high atmosphere to produce an aerothermodynamic environment like that to be experienced by an ASTV. The vehicle should fly a roll-controlled trajectory to obtain realistic flight-performance data. Recovery is also important for postflight inspection and analysis of the TPS.

Flight Tests, the Aeroassist Flight Experiment

Flight test experiments are needed to identify the various processes occurring during nonequilibrium flow. Valid tests cannot be done on the ground because the reaction time of various important interrelating dynamic processes compared to the flow time is important. Experiments with small models in arc jets and ballistic tunnels cannot simulate these interactions and show the overall flow field simultaneously. A large test vehicle is required so that the standoff distance of the shock wave will be adequate for the nonequilibrium conditions to be distinct from the boundary layer, as will be the case with the ASTV. Also, it must have a TPS that will not contaminate the shock-layer flow; that is, the TPS must not ablate. The vehicle must be able to simulate a return mission from GEO to LEO, and travel through the Earth's upper atmosphere at a speed sufficient to induce distinct and measurable phenomena. The test vehicle must also be recoverable to allow for postflight analysis of the experiment, particularly the thermal protection materials.

This is the AFE, a productive, timely, and necessary step toward the ASTV fleet of the future. The reality of substantial chemical nonequilibrium in the flow field has led to the initiation of this AFE test program. The AFE is designed to collect a data base to develop and validate computational models for future ASTV design. This experiment consists of a spacecraft designed to function as an aerobrake. The AFE will be placed in orbit by a Space Shuttle Orbiter at an altitude used by the Orbiter and then will be driven by rocket propulsion into the Earth's upper atmosphere to simulate a return from GEO. The aeropass will be approximately 5000 miles long across the Pacific Ocean. The mission profile is designed to simulate important features of an actual ASTV maneuver. These include the influence of shock-layer nonequilibrium on the levels of radiation and convective heating, the influence of viscous and real gas effects on the aerodynamic characteristics of the vehicle, the ability of thermal protection materials covering the surface of the aerobrake to maintain low levels of catalytic activity, and the effects on guidance arising from unpredicted variations in air density. These key issues can be resolved only by obtaining flight test data.

The AFE is essentially an adequately large, instrumented platform whose primary purpose is to acquire fundamental aerothermodynamic data at the range of flight velocities and altitudes where an ASTV will operate. AFE is not a design for an ASTV. It is a means to provide the basic scientific data for such designs. That valuable data about the behavior of an ASTV flow environment can be obtained by instrumented bodies traveling at high speeds was demonstrated early in the 1970s by the Planetary Atmospheres Experiments Test (PAET). The entry vehicle was launched in June 1971 by a four-stage Scout rocket from Wallops Island, Virginia, to enter the atmosphere near Bermuda. Basically, the experiment demonstrated that the composition and structure of an unknown planetary atmosphere can be determined by measuring the interactions between an entry probe and the atmosphere. Of importance to the AFE mission, PAET showed that instruments can be designed to obtain important scientific information about atmospheric processes caused when a blunt body travels at hypersonic velocity in the rarefied upper atmosphere, and that radiation from the shock layer can be analyzed in detail to identify and quantify the important radiating gas species.

The AFE is a recent new-start program of NASA. An Aerocapture Technology Working Group was formed in 1980, composed of representatives from nearly all NASA centers. In 1982 this group established the need for a flight test. Early in the 1980s NASA's Aeroassist Working Group identified the specific technologies and technical issues which must be addressed to meet the challenge of routine use of aeroassist to modify orbits by braking or maneuvering. Important milestones were reached during subsequent years. An AFE Steering Group was formed in 1983, and the initial concept was defined by November of the following year.

An initial Project Initiation Agreement was signed in 1985, and the Science Review Board established justifications for the AFE, namely, that technology development required for a future ASTV must precede the system definition and development. The nonequilibrium air environment required for understanding aerobraking and system performance can be achieved only in large-scale flight tests at sufficiently high velocities.

The Project Initiation Agreement was updated in 1986. This was followed a few months later by publication of an integrated science plan. In October 1987 the AFE program was given new-start approval, and a detailed project plan was published. The schedule established is for a flight test of the AFE in 1995.

Objectives of the Aeroassist Flight Experiment

The Science Review Board in a Science Rationale Document stated that the objectives of the AFE mission were to provide benchmark data to define the environment in which an ASTV must fly; radiative and convective heating effects both to the forebody and to the afterbody region of a blunt aeroshell; and the means to verify computational flow-field codes both through specific measurements of gas and wall parameters and through performance data obtained along its trajectory. An additional objective identified is to demonstrate the performance of state-of-the-art guidance techniques for flying a vehicle with a low lift/drag ratio (LID) in a variable-density atmosphere. It is known that the density of the upper atmosphere varies from location to location and from time to time somewhat unpredictably. Such variations could adversely affect the guidance and control of an ASTV moving through the upper atmosphere and lead to its being deflected from its path unless corrections were made. Finally, the performance of candidate materials and surfaces for a TPS in the ASTV environment will be investigated.

Management of the Aeroassist Flight Experiment

NASA Headquarters, Washington, D.C., administers the AFE program, reports on the program to NASA management, and is the focal point for all external relations. It is also responsible for technical and financial management of the AFE program. The elements of the program include the aerobrake, the carrier vehicle, instrumentation, ground and airborne support equipment, and system test operations.

A Science Steering Group has been appointed by NASA Headquarters to provide advice on the program. It consists of scientists from NASA, universities, and industry.

Several NASA centers participate in the program under the direction of the Marshall Space Flight Center, Huntsville, Alabama, which has responsibility for project management. The Marshall project office has the responsibility for developing the AFE, integrating the total program, and operating the flight test.

Langley Research Center, Hampton, Virginia, is responsible for the development of certain instruments and for overall integration of the science experiments. The Project Scientist at the Center is responsible for identifying science experiments and resolving issues regarding the experiments, and for ensuring that all the science objectives are met. Langley Research Center is also responsible for defining and coordinating the ground-based test program, including computational fluid dynamics (CFD), that supports the project office in planning the mission.

Johnson Space Center, Houston, Texas, is responsible for developing the aerobrake and some of the instrumentation. It also assists in developing algorithms for the guidance, navigation, and control software. The Center participates with other Centers in developing codes for CFD used to guide the design of the aerobrake and carrier vehicle.

Ames Research Center, Moffett Field, California, supports the AFE program in aerothermodynamics and thermal protection, and is responsible for some of the science experiments. The Center also supports the program in cooperation with other centers in mission planning and analysis, ground-based testing, and CFD analysis. It provides advanced computational work in support of the development of codes for the design of ASTVs.

The resolution of the major questions about the technology of aeroassist by the AFE program is discussed in section 4, where the various flight instruments are described.

SECTION 3: THE AEROASSIST FLIGHT EXPERIMENT (AFE) PROGRAM

Development

The AFE will be carried to, and recovered from, LEO by the Space Shuttle Orbiter. The test vehicle will be released on orbit at a nominal altitude of 160 nautical miles, and after appropriate on-orbit checkout will be accelerated downward into the Earth's atmosphere to a velocity of 33,800 feet per second at the nominal atmospheric entry point of 400,000 feet. This simulates a return from GEO. The perigee (closest approach to Earth) of the spacecraft's trajectory occurs at an altitude of approximately 250,000 feet above the Earth's surface. After leaving Earth's atmosphere at the end of the test flight, the test vehicle will be recovered by the Orbiter for return to Earth.

AFE development officially began in fiscal year 1988 aiming for a launch readiness date of 1995. A substantial part of the design of the spacecraft and instruments will be by civil service personnel at the various NASA Centers involved in the program. The aerobrake will be built by Johnson Space Center. The carrier vehicle will be designed by Marshall Space Flight Center, and McDonnell Douglas has been selected as the fabricator. Most of the other fabrication, assembly, and test of the AFE will be by contractors.

The AFE is a single-mission project. Its primary aim is to gather basic scientific data about the aeroassist environment. The spacecraft is defined as a class B payload for the Shuttle. Existing designs for subsystems will be used wherever possible with upgrades to high-reliability parts because instruments will not be duplicated. The basic TPS on the aerobrake will be the same type of tile used in the Space Shuttle Orbiter. No major technological developments or advancements in the state of the art are required to implement the AFE.

The AFE program requires the development of computational capabilities, ground-based testing with ballistic ranges and arc jets, and development of instruments. Limited redundancy of systems requires that high reliability be assured to achieve the same probability of success as a spacecraft with redundant systems.

Several major areas of NASA activities relate to and support the AFE. A development program for thermal protection materials and coatings at Ames Research Center is important to the project. At Langley Research Center, ground-based testing uses wind tunnels. Arc-jet and ballistic range tests take place at Ames Research Center and Johnson Space Center. Development of CFD is proceeding at these Centers as well as at Marshall Space Flight Center. The TPS research and the CFD analysis are funded separately from the AFE program.

The Flight Mission

The AFE vehicle is mounted on a spacecraft support structure in the bay of a Space Shuttle Orbiter which carries it into LEO (Figure 3-1). The vehicle is deployed from the payload bay and completes almost one orbit of the Earth while systems are checked and the AFE vehicle is maneuvered to the attitude needed for entry (Figure 3-2). A solid-propellant rocket motor is then fired, accelerating the AFE vehicle along a path that will carry it into the upper atmosphere for the hypervelocity test pass. When the desired velocity has been reached, the rocket motor casing is jettisoned and separates from the test vehicle.

The passage through the atmosphere (Figure 3-3) lasts approximately 10 minutes, during which the AFE vehicle descends to an altitude as low as about 250,000 feet. The descent into the atmosphere is at nearly constant velocity. The AFE vehicle then levels out and is decelerated at a roughly constant altitude. The most important data-gathering period is that during the transition from constant velocity to constant altitude. This is the region where heating peaks. During this period no maneuvering jets are fired unless they are required to save the mission. This quiescent period ensures that the wake flow is not contaminated by rocket exhaust gases. After the scientific and technical data have been gathered, the maneuvering jets will be used again to guide and control the vehicle through the atmosphere at hypersonic speeds. Later, when the AFE vehicle emerges from the atmosphere back into space, the maneuvering jets are used to circularize the orbit so that the vehicle can be recovered

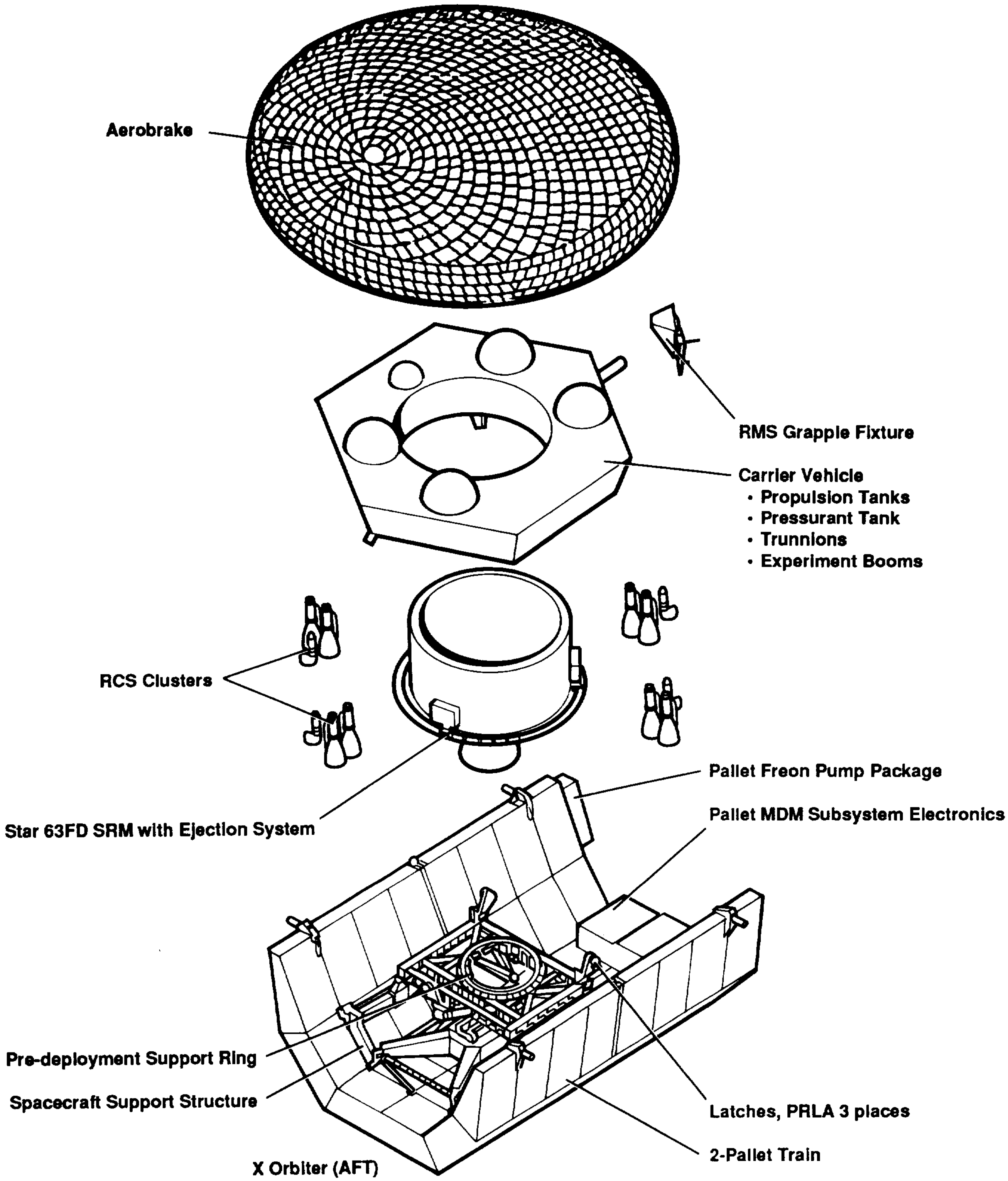

Figure 3-1. The aerobrake, the carrier vehicle, the solid-propellant rocket motor, and the supporting structure by which the spacecraft is carried on the pallet within the Space Shuttle Orbiter's cargo bay.

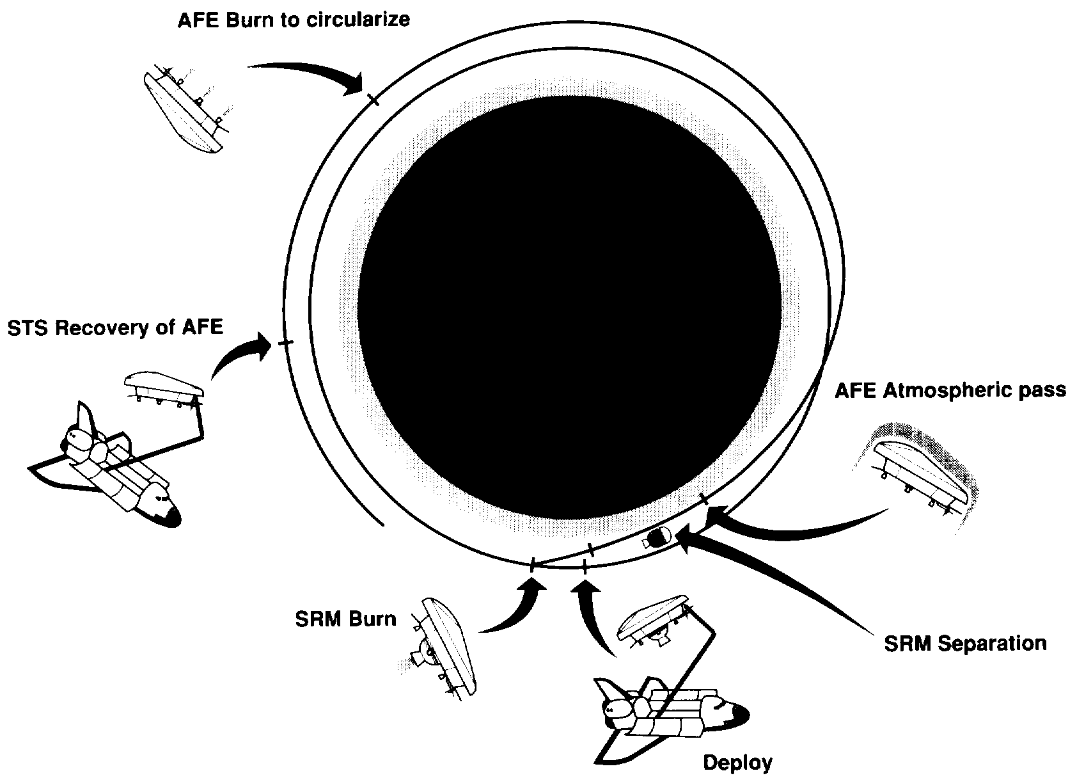

Figure 3-2. Operational sequence of the AFE mission with launch and recovery by the Orbiter.

by the Shuttle Orbiter. The sequence of deployment to recovery requires about 13 hours.

Recovery

Some mission objectives require recovery and return to the laboratory of the AFE vehicle. This is required to answer questions which cannot be instrumented for, and therefore require post-flight inspection and testing. This activity will provide the final set of data required to complete the technology data base to be provided by AFE for aeroassisted return from GEO and from lunar missions.

Primary technological benefits of recovery are related to the TPS experiments. Since ground-based experiments cannot duplicate the combined convective and radiative environment that ASTVs will experience in flight, the performance and re-flight capability of the baseline and advanced TPS materials can best be assessed through post-flight examination. This assessment will concern questions relative to the performance of a rigid TPS, such as coating behavior, (bubbling and melting, for example); optical property changes; and tile shrinkage and deformation. These cannot be assessed by the discrete thermocouple measurements that are the source of the flight data.

Other issues requiring post-flight examination are

1. The performance of the nonrigid TPS, as well as that of the associated adhesive.

2. Inspection of temperature-sensitive labels that will determine peak temperatures at many locations on the aerobrake structure to assess the impact of TPS on structure thermal performance.

3. Critical data interpretation considering how the instruments have been affected by the TPS (such as tile slumping around pressure ports and radiometer windows, thermocouple signal anomalies, and radiometer window contamination due to TPS material outgassing).

4. Post-flight calibration of experiment sensors (radiometers, pressure transducers, and accelerometers) to optimize critical data sets.

Recovery of the AFE vehicle will provide invaluable data from which unpredicted phenomena can be identified and resolved, as well as data to enhance the technology

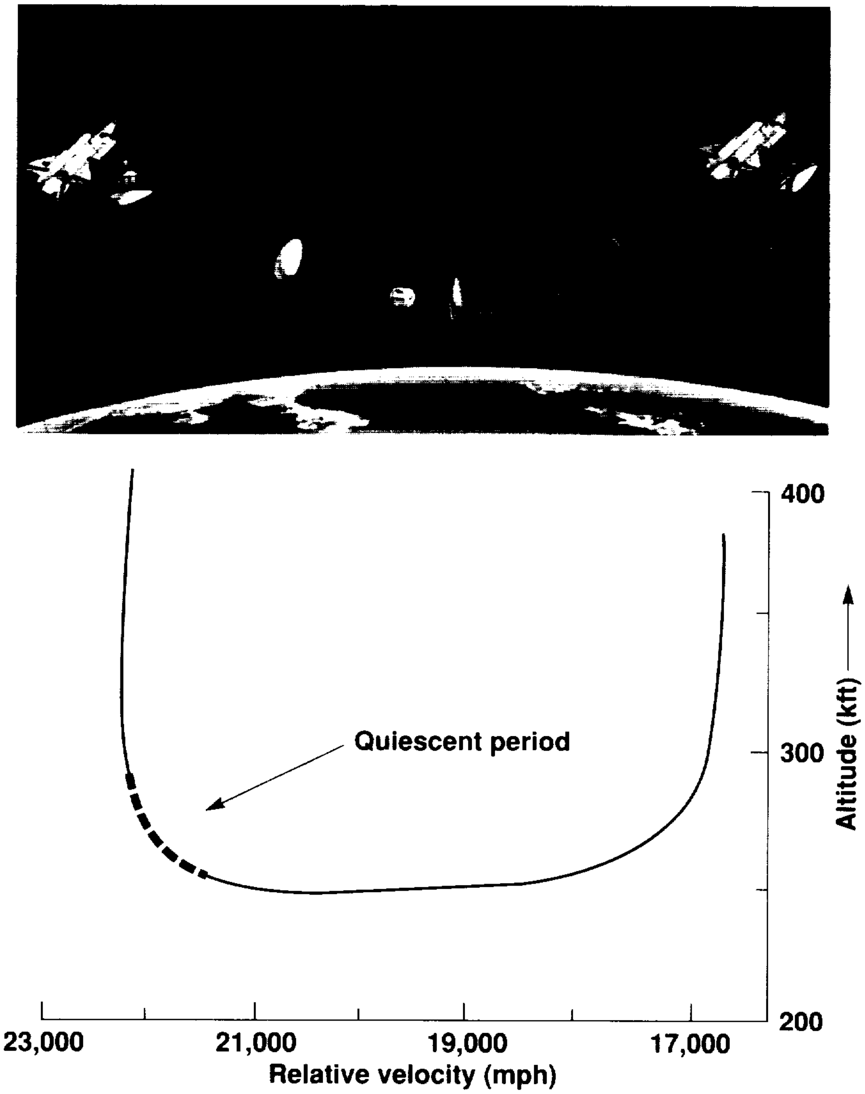

Figure 3-3. The flight regime of the AFE and its passage through the upper atmosphere. The altitudes and relative velocities are shown in the line diagram.

data base relative to predicted phenomena. This has been the experience with the recovery and post-flight inspection activities of the Space Shuttle Orbiter program. The Orbiter was, and continues to be, modified as a result of data and observations obtained only from post-flight inspections. It is expected that the "new" flight regime associated with ASTV will yield results that a priori instrument design will not obtain. The results therefore can be resolved only through post-flight evaluations. Consequently, the AFE objectives mandate recovery of the vehicle. Cost analyses indicate that this recovery of the AFE will be about 1% only of the total program's cost.

The ASTV Design Code Development

The motivation of the AFE is to develop the data base to support the design of a future ASTV. This includes validation of CFD codes. To gain maximum benefit from the flight experiment for this purpose, it is necessary to have a strong program in place for code development and phenomenological modeling. The codes and physical models will be necessary to interpret and evaluate the flight data and the flight data will, in turn, be used to validate the codes. The validated codes will be used in the analysis and design of future ASTVs. Particular code development emphasis is needed on the entire thermochemical nonequilibrium flow field, i.e., the forebody region, the flow over the shoulder, and the unsteady flow in the base and wake regions. It is also important to further develop the codes to incorporate radiation fluxes.

Phenomenological models are in existence for the compressive flow regions, but they require the AFE data for improvement and validation. New models are needed for the expanding flow regions where there are inversions in energy level populations. And the present radiation codes need validation and must be incorporated into the flow-field codes.

The AFE instruments are designed to generate the data base required for the code development. The surface pressure and temperature measurements relate to vehicle performance and state of the gas in the AFE flow field. The surface heating rates, both convective and radiative, can be related to the state of the flow-field gas, surface catalytic effects, and the radiative energy transport of the flow field. The spectral content of the flow-field radiation is a potent indicator of the flow-field gas state. The frequency spectral content of the wake unsteadiness is a fundamental quantity of the wake dynamics, and a valid CFD model must be able to reproduce these characteristics. All of these properties must be derived from the AFE flight event for development of efficient ASTV design codes.

A coordinated program has been initiated to develop codes needed to interpret and utilize the AFE data. This program also involves upgrading, and in some instances reactivating, some of NASA's high-enthalpy hypervelocity test facilities, such as shock tunnels and ballistic ranges, to be used for aerodynamic and aerothermodynamic testing. It also includes a focused computer code development program with direct application to the AFE's configuration and flight trajectory. The technology resulting from this program will be sufficiently mature when the AFE is performed to permit our gaining maximum benefit from the flight data. When the program is completed, a validated computational tool will exist, capable of use to achieve reliable design of ASTVs for return from GEO or from the Moon.

The next section of this publication describes the AFE vehicle and the instruments used to gather the important data concerning the hypersonic flight environment.

SECTION 4: THE AFE VEHICLE AND ITS INSTRUMENTS

There are two main approaches to designing a vehicle capable of entering an atmosphere and using that atmosphere to dissipate kinetic energy. One is a high L/D approach where convective heating dominates; the other is a low L/D approach where radiative heating dominates. The high L/D vehicle has a pointed shape; the low L/D vehicle has a blunt shape (Figure 4-1). High L/D vehicles are expected to be required for high maneuverability; e.g., in a manned mission to Mars requiring accurate control for landing at a specific location on the planet. Some studies, however, have suggested that low L/D aerobraking vehicles can be used for Earth return from Mars as well as for Mars landings.

For an AFE design a low L/D vehicle has advantages in investigating hypersonic flow conditions because the blunt shape pushes the shock front ahead of the vehicle and forms a sufficiently thick shock layer to evaluate nonequilibrium flow with minimum merging with cooler flow near the surface or contamination by the vehicle itself. Thus the basic physical principles of hypersonic flow can be investigated and defined for the blunt shape which is likely to be a model for a full-scale ASTV.

Various vehicle concepts (Figure 4-2) were considered for the ASTV. These included an aerobraking tug, an aeromaneuvering orbit-to-orbit shuttle, and a lifting brake. The lifting brake has received the most attention during the past decade because it requires less weight than the other approaches, thereby allowing a greater payload. The lifting brake has a large frontal area which produces a high drag. This allows deceleration to take place at a high altitude in the atmosphere. In turn, this permits the peak heating to be kept within limits that can be tolerated by lightweight heat-shield materials. The AFE vehicle is a lifting-brake vehicle.

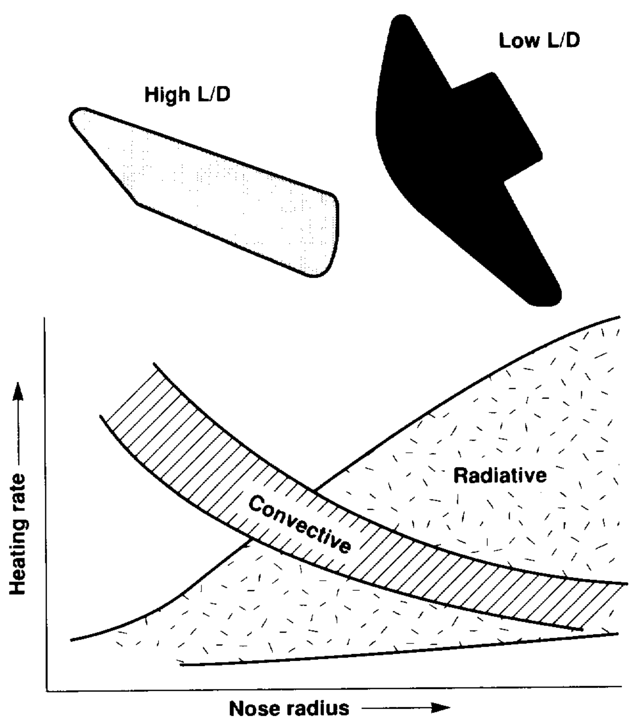

Figure 4-1. Extreme classes of aeroassisted vehicles based on their ratios of lift to drag.

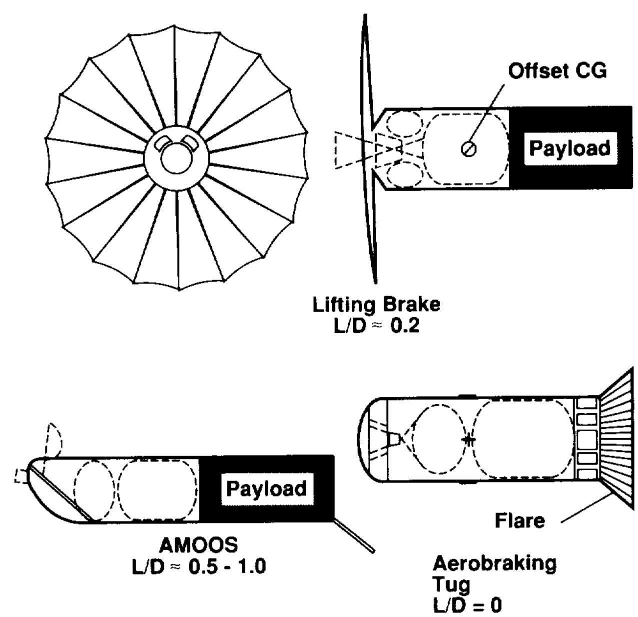

Figure 4-2. Various vehicle concepts that have been considered for ASTVs.

The basic control scheme for the lifting-brake AFE is to fly at a constant trim angle of attack while rolling the vehicle as required to direct the lifting force in the appropriate direction. This lifting force is used primarily to correct the trajectory for unpredictable variations in atmospheric density, which could cause the vehicle to follow a wrong trajectory. The lifting force is also used to place the trajectory higher in the atmosphere than would be possible with a purely ballistic flight, without the AFE vehicle exiting too quickly and not dissipating the required amount of kinetic energy for it to enter LEO.

Configuration of the AFE Vehicle

The AFE (Figure 4-3) is designed to test the blunt, lifting-brake concept using a roll-controlled guidance system. The diameter and effective nose radius are sufficient to produce the thick shock layer while fitting within the payload bay of a Space Shuttle Orbiter which will carry the AFE vehicle into orbit.

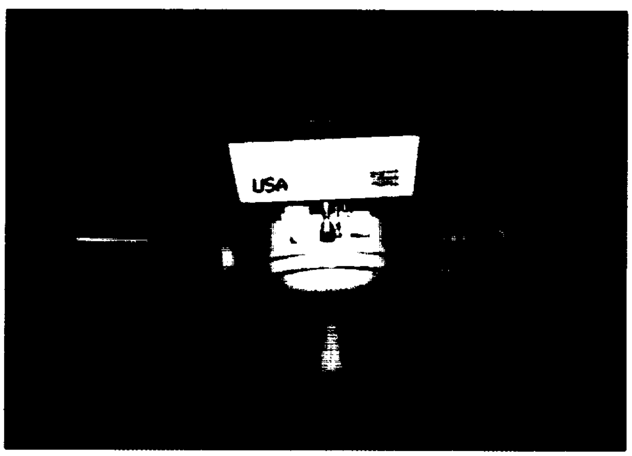

Figure 4-3. The AFE, shown here in a computer-generated concept, is designed to use the blunt-nosed, low L/D configuration.

The configuration resulted from a design study conducted at Johnson Space Center. The AFE's aeroshell is an elliptical cone blunted by an ellipsoidal nose. The cone is raked off at an angle of 17 degrees relative to the axis normal. The base profile in the rake plane is circular. The aeroshell's diameter is 14 feet.

The aerobrake support structure (Figure 4-4) is a low-temperature aluminum structure of the type used frequently in aeronautical construction. This instrumented structure is covered with a layer of fibrous refractory

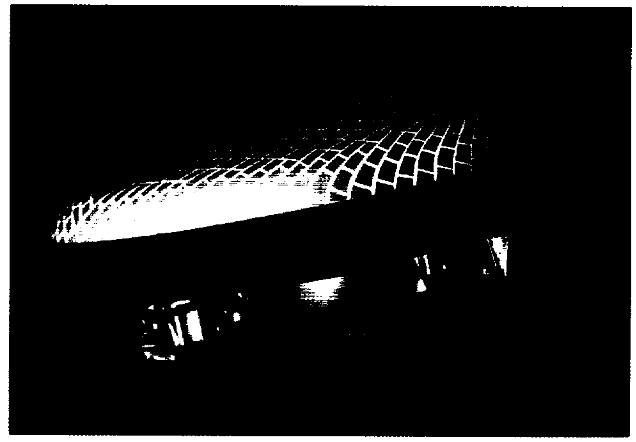

Figure 4-4. This side view of a model of the AFE shows the special shape of the aerobrake structure to provide maneuverability as well as braking.

composite insulation tiles such as are used in many areas of the Space Shuttle Orbiter. The aerobrake weighs 725 pounds. The total weight of AFE without its solid propellant rocket motor is 4,100 pounds. It is important to note that the AFE is not intended to demonstrate lightweight construction, but is essentially an instrumented platform to acquire aerothermodynamic flight data.

The aerobrake is mounted on a hexagonal carrier vehicle whose diameter is less than that of the rake plane. The aerobrake thus overhangs the carrier. The carrier is a box-like spacecraft structure housing the reaction-control system, data-management system, communications, some instruments, and a solid-propellant rocket motor. The latter is a Thiokol Star-63 unit which develops the thrust needed to push the AFE vehicle into Earth's atmosphere at a velocity comparable to that which would be experienced by an ASTV returning from geosynchronous or cislunar orbit.

The AFE is fitted with a remotely manipulated system grapple fixture to permit it to be deployed and retrieved by the Space Shuttle Orbiter. Within the Orbiter's cargo bay, the AFE is carried on two standard Spacelab pallets.

Instrumentation of the AFE

The proposed experiments to be carried by the AFE use instrumentation located on the aeroshell and on the afterbody of the vehicle (Figure 4-5). These experiments are summarized in Table 1.

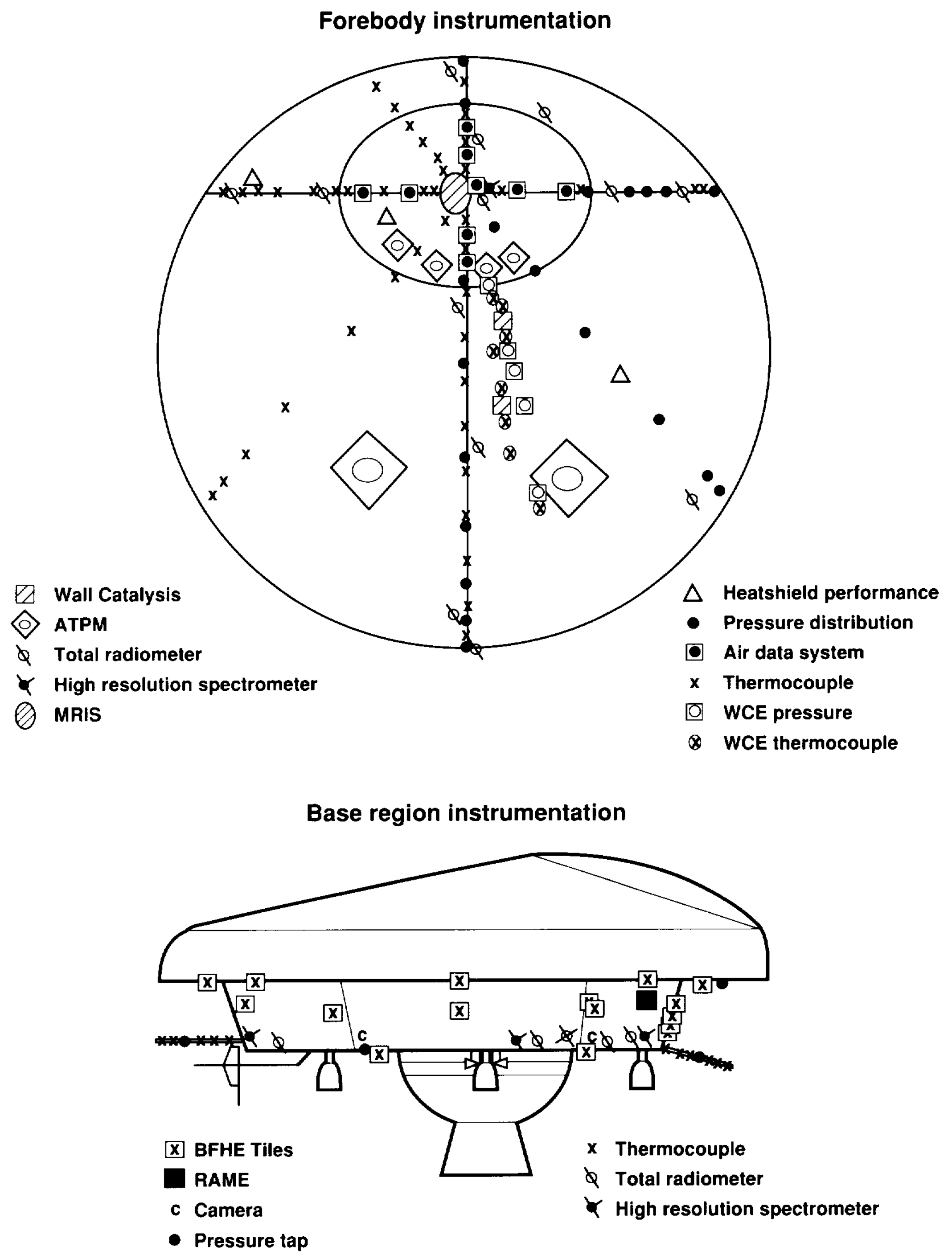

Figure 4-5. Locations of the many instruments to be used in the experiments carried aboard the AFE.

Table 1. Proposed AFE Experiments

Name (Acronym)	Principal Investigator	Center
1 Radiative Heating (RHE)	R. A. Craig	ARC
2 Wall Catalysis (WCE)	D. A. Stewart	ARC
3 Forebody Aerothermal Characterization (FACE)	L. Hartung, D. A. Throckmorton	LaRC
4 Pressure Distribution/ Air Data System (PD/ADS)	L.Gibson	LaRC
5 Base Flow and Heating (BFHE)	C. D. Scott, M. Jansen	JSC
6 Afterbody Radiometry (ARE)	W. C. Davy, A. W. Strawa	ARC
7 Microwave Reflectometer Ionization Sensor (MRIS)	R. Neece, P. Gnoffo	LaRC
8 Alternate Thermal Protection Materials (ATPM)	M. A. Covington, D. Kourtides	ARC
9 Heat-Shield Performance (HSP)	D. E. Cagliostro, S. White	ARC
10 Aerodynamic Performance (APEX)	C. Cerimele	JSC
11 Rarefied Flow Aerodynamic Measurement (RAME)	R. C. Blanchard	LaRC

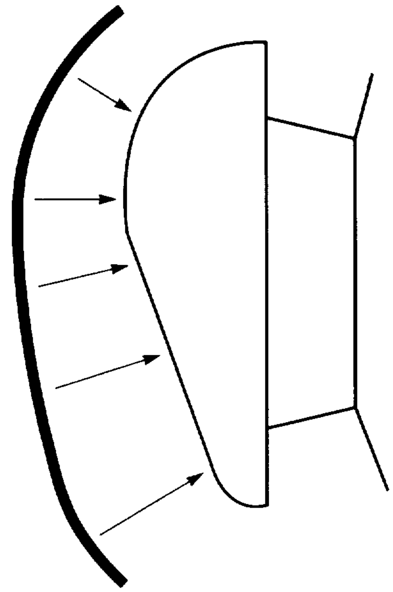

Figure 4-6. The radiative heating experiment.

The **Radiative Heating Experiment** uses a number of spectrally integrating radiometers placed on the forebody to measure the distribution of radiation from the shock layer which reaches the aerobrake (Figure 4-6). A spectrometer will be located near the stagnation region, the region at the front of the AFE where the flow is virtually at a standstill with respect to the AFE. Another spectrometer will be located nearby, but in a cross-flow region. These instruments will be used to identify the relative contributions of various gas species in the radiation to the wall of the aerobrake. Some of these species may reach a temperature of 45,000 K during the entry of an ASTV. Characterizing these species is important to building a data base for the design of an efficient ASTV.

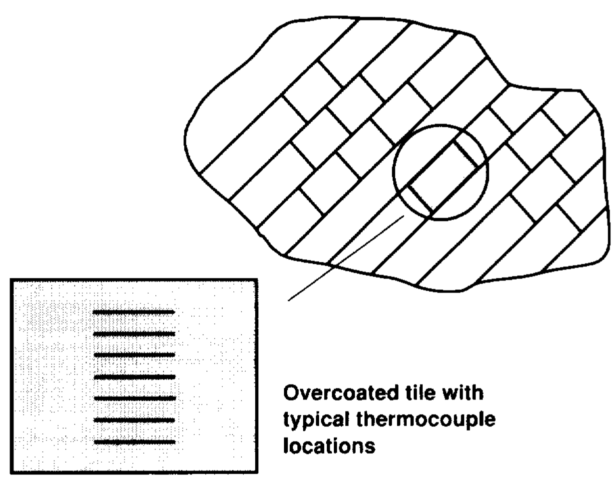

Figure 4-7. The wall catalysis experiment.

The **Wall Catalysis Experiment** will use a highly efficient catalytic coating on baseline TPS tiles at several locations on the forebody heat shield (Figure 4-7). By analyzing the heat-transfer data at these locations compared to baseline heating, the experimenters will determine the ability of coatings to change convective heating rates, and may also estimate the nonequilibrium nature of the flow in the boundary layer.

The **Forebody Aerothermal Characterization Experiment** uses thermocouples embedded below the glass-coated surface of the thermal protection tiles (Figure 4-8) to record the surface temperature of the heat shield during passage of the AFE vehicle through the atmosphere. This permits the local rate of heat transfer to be calculated. The convective heat-transfer rate can be

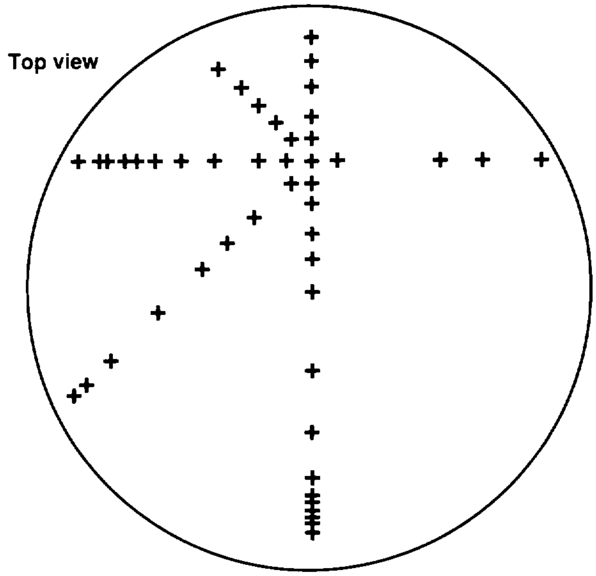

Figure 4-8. Thermocouple locations on FACE experiment.

extracted from the local heating using information from the Radiative Heating Experiment. This information is needed in the data base for the design of an efficient ASTV. The data will be used as fundamental information to validate codes used in CFD computations.

The **Pressure Distribution/Air Data System** measures surface pressure at locations on the forebody (Figure 4-9) to help analyze the flow and determine the attitude of the vehicle and the dynamic pressure on the aerobrake during flight. The data will provide fundamental information to validate codes used in CFD. Pressure data will be used to determine angle of attack, angle of sideslip, and free-stream dynamic pressure. The air data will be used to define the reference flight environment.

The **Base Flow and Heating Experiment** uses thermocouples and pressure transducers together with an imaging system mounted in the aft flow region of the spacecraft (Figure 4-10). Some instruments will be mounted on booms projecting into the flow region. The experiment is aimed at studying the nature of the base flow throughout the AFE's path through the atmosphere in an effort to resolve the complexities of this flow. The results will be used to define the shear layer, including the turning angle of the high-speed outer flow, and the location of the boundary which separates the high-energy outer flow from the low-energy recirculating inner flow. They will also be used to assess afterbody thermal loads.

The **Afterbody Radiometry Experiment** measures the volume radiation of the gas in the wake with spectral

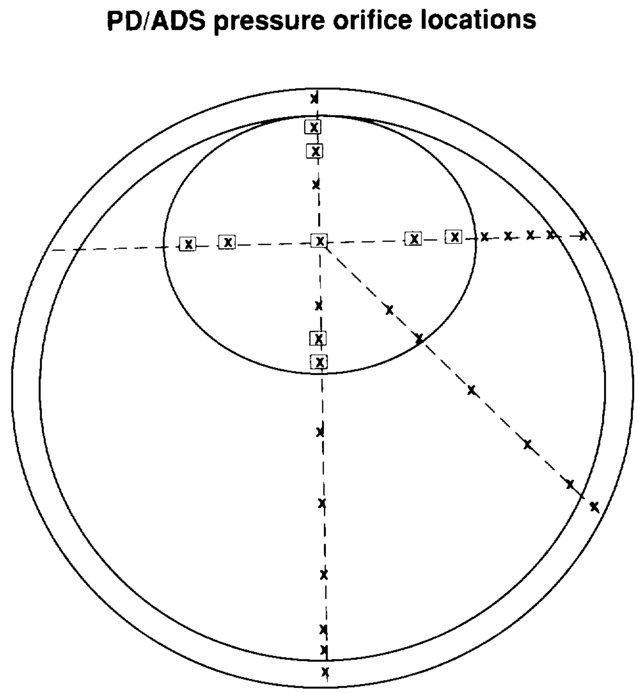

Figure 4-9. The pressure distribution/air data system.

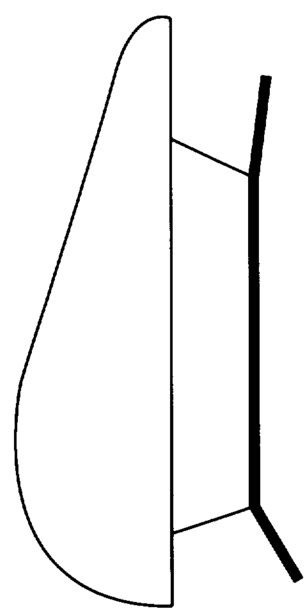

Figure 4-10. The base flow and heating experiment.

and integrating radiometers (Figure 4-11). The data will be used to determine the initial state of the wake flow gases and the chemical state at the downstream compression zone, and to determine the total radiation flux at selected locations on the afterbody. An additional instrument is proposed to determine the dynamic behavior of the wake.

The **Microwave Reflectometer Ionization Sensor** measures the reflected power of microwave signals beamed outward from the vehicle (Figure 4-12) at four different frequencies. Significant reflected power will be an indication of free electrons reaching critical density—from which it can be determined the time of onset and disappearance of critical densities, as well as locations, in the shock layer. Such data will be important in supporting code validation of flow-field chemistry.

The **Alternate Thermal Protection Materials** experiment replaces the baseline TPS material at selected locations on the forebody with test samples (Figure 4-13) of various advanced and developmental thermal protection materials. The samples are instrumented with thermocouples to measure their heating. Postflight inspection is required to evaluate their performance.

The **Heat Shield Performance Experiment** measures the performance of the baseline tiles using thermocouples on the surface and buried within the tiles (Figure 4-14). Of particular interest is heating in the gaps between the tiles in the high-pressure-gradient region around the skirt of the heat shield where these gaps are somewhat shallower than those in the Space Shuttle Orbiter's TPS, and in the stagnation region where heating is most severe.

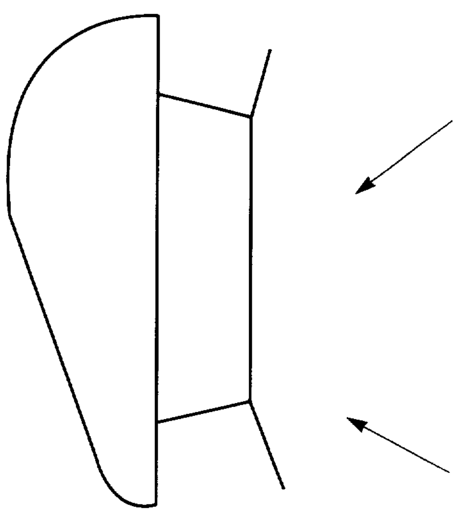

Figure 4-11. The afterbody radiometry experiment.

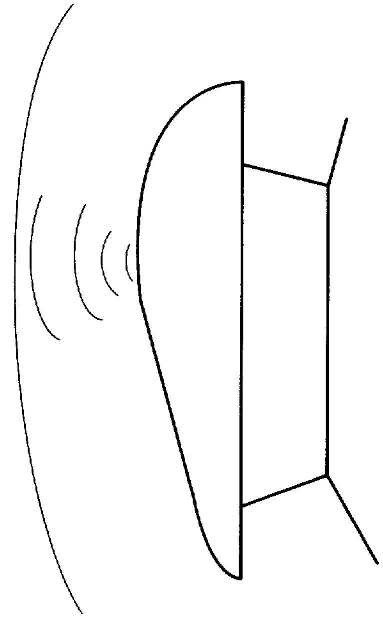

Figure 4-12. The microwave reflectometer ionization sensor.

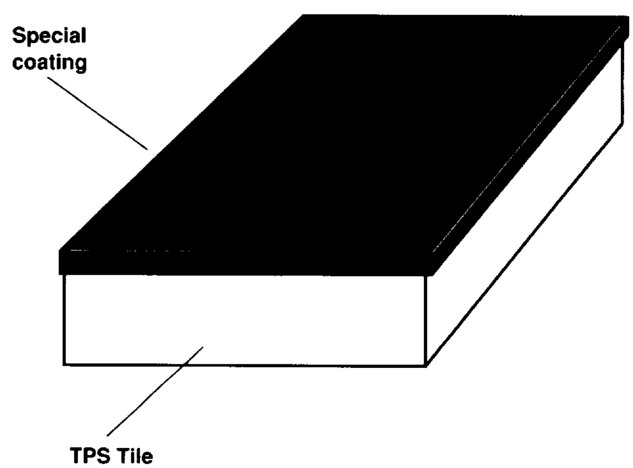

Figure 4-13. The alternate thermal protection materials experiment.

The **Aerodynamic Performance Experiment** will determine the values of the aerodynamic coefficients for lift, drag, and pitching moments (Figure 4-15) during the flight through the denser part of the atmosphere. This will provide a set of benchmark data which can be compared with predictions. Avionics accelerometers and angular rate gyroscopes of the guidance, navigation, and control system of the spacecraft will be used to derive aerodynamic forces and moments during the flight.

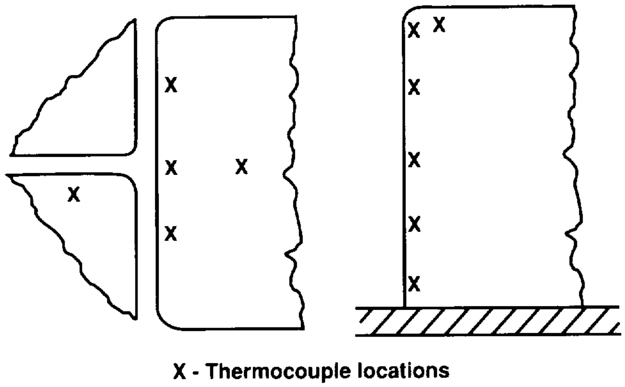

Figure 4-14. The heat shield performance experiment.

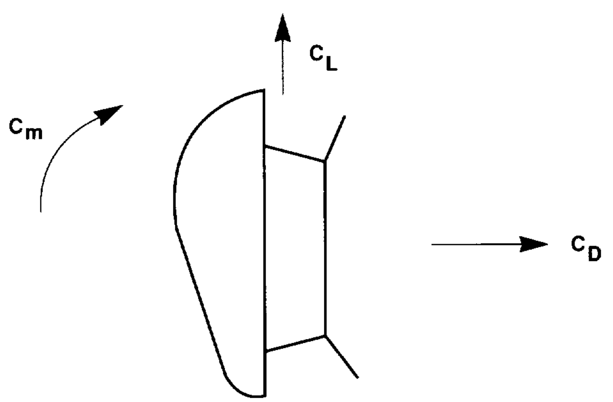

Figure 4-15. Aerodynamic performance experiment.

The **Rarefied Flow Aerodynamic Measurement Experiment** uses high-resolution accelerometers and rate gyroscopes aligned to the axis of the AFE to provide data in the transition and free molecular flow regimes (Figure 4-16) at altitudes above 300,000 feet, which are beyond the capability of the basic AFE avionics measurements. The data will be used to determine aerodynamic coefficients of the vehicle in these low-density viscous flight regimes. Ultimately, the experiment will provide data to validate spectral benchmark computer codes which are capable of bridging the gap between describing the aerodynamics of an "orbiting" spacecraft and of a "flying" spacecraft.

A major challenge in designing these experiments was in the placement of the instruments and the shaping the vehicle so that the flow past the AFE is not contaminated in ways that will invalidate the data. Another challenge has been that of making sure that the instruments can take measurements in situ when the carrier vehicle is moving at hypersonic velocity through the atmosphere. Most earlier in situ atmospheric measurements from spacecraft—such as Viking Landers and Pioneer Venus Probes—were made when the spacecraft was traveling slowly through an atmosphere. In this respect, for example, there will be several scientific spinoffs of new technology from AFE. One is the development of space-qualified instruments, such as radiometers and the microwave reflectometer ionization sensor, capable of gathering data while moving at high speed through an atmosphere to allow in situ atmospheric measurements at high speeds for planetary exploration probes. AFE, building on PAET, Project FIRE, and ongoing technology programs of NASA, will also introduce planetary exploration techniques comprising both the new instruments and the computational fluid dynamics to predict conditions in atmospheric gases.

Expected results of the experiments and their importance to future space transportation systems and space missions are described in the next sections of this publication.

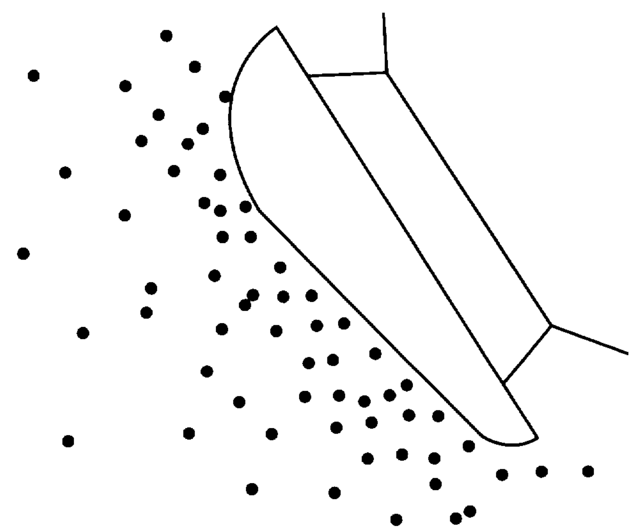

Figure 4-16. The rarefied flow aerodynamic measurement experiment.

SECTION 5: EXPECTED RESULTS FROM THE AFE

In meeting its mission objectives, the AFE program will resolve the major questions about radiative heating at hypersonic velocities. It will determine the effects of wall catalysis. This is very important for designing vehicles capable of traveling at high speeds in the upper atmosphere where nitrogen and oxygen atoms may play important roles in heating due to recombination at the wall of the aerobrake. Advanced TPS materials will be evaluated. Several different thermal control coatings will be tested on the basic TPS tiles. The wake flow and base heating will be defined, and the ability to control the vehicle in its flight through the atmosphere will be assessed. The new data base produced from the AFE program will provide a basis to develop and verify codes to be used in the computer design of other hypersonic vehicles, including the ASTV space transportation system.

Currently there are alternative interpretations of available data on the radiation from nonequilibrated shock layers, and the amount of radiation that will reach the wall of the TPS when no ablation gases are present and the shock layer is thick. The AFE program will provide data for a correct interpretation through its Radiative Heating Experiment.

At higher velocity and greater altitude than the region of main deceleration of the Space Shuttle Orbiter, nitrogen and oxygen dissociation, ionization, and recombination will affect the heat input to the TPS system. The magnitude of this effect will be determined by the AFE mission, and the measured heat-transfer rates with various wall coatings are expected to provide guidelines for designing materials having low catalytic activity coating for the ASTV.

Testing of advanced rigid and flexible thermal protection materials is expected to determine whether flexible ceramic blanket materials will perform adequately and whether new, high-temperature, rigid ceramic tiles can be used in the hypersonic entry environment. Reflective coatings will be tested that are expected to reflect more of the nonequilibrium radiation. These data will come from the Alternate Thermal Protection Material Experiment.

The base region heating and the flow environment behind a blunt-nosed body moving at hypersonic speeds in a low-density atmosphere is currently poorly understood. AFE will clarify the situation by providing information about the significance of wake radiation and ionization, and the distribution of convective heating over the aft portion of the aerobrake structure. These results will help define the safe ASTV payload envelope. Information of importance will be derived from the Base Flow and Heating Experiment and from the Afterbody Radiometry Experiment.

By flying AFE through the upper atmosphere while measuring its aerodynamic parameters and observing the ability of the guidance, navigation, and control system to direct its trajectory, designers will obtain much needed data about the performance of an aerodynamic, roll-controlled, lifting brake and the abilities of such a vehicle to handle dispersions in navigation and guidance. The necessary data will be derived from the Aerodynamic Performance Experiment, the Rarefied Flow Aerodynamic Measurement Experiment, and the Air Data System Experiment.

Because of the limitations of ground-test capability, ASTV design must be based primarily on computational methods. But even the most powerful supercomputers are useless unless they can be provided with reliable basic data with which to make computations. The ASTV presents a number of computational challenges which require a significant advancement over existing codes and procedures for predicting aerothermal loads and thermal and structural responses. For example, in CFD there is a good understanding of the important flow physics involved in thermochemical nonequilibrium, finite-rate chemistry, and molecular excitation, but input data are lacking to validate the codes in practical applications.

Basic data to confirm, develop, or validate computer models of high-speed flow are prerequisite to the design of the future ASTV fleet. Such data are expected to be derived from the measurements made from the AFE platform. Instruments involved in providing these data include the Pressure Distribution Experiment, the Forebody Aerothermal Characterization Experiment, the Microwave Reflectometer Ionization Sensor Experiment, the Radiative Heating Experiment, and the Afterbody Radiometry Experiment.

As discussed earlier, the AFE will use a nonablating heat-shield material similar to the material used on the Space Shuttle Orbiter. This is an insulating ceramic material with a black coating to radiate away the heat. This kind of heat shield would be suitable for ASTVs used for orbital changes in the vicinity of the Earth (for example, from GEO to LEO, or return from the Moon to LEO) and for orbital capture at Mars. However, the arrival at Earth from a planetary mission requires an ASTV with an ablative heat shield because of the much higher speeds. The presence of ablation on an ASTV would distort the flow field to such an extent that computational validation would not be possible on the basis of the AFE results. An ablating aeroassist flight experiment will, however, be required to complement the results of AFE. Although the AFE data will not directly apply to an ASTV returning from a Mars mission, they are needed to develop experiments for and interpret results from an advanced aeroassist experiment to support the design of such an interplanetary ASTV.

SECTION 6: INTO THE FUTURE

Information gained from the Aeroassist Flight Experiment program will be of enormous economic benefit to the United States in keeping abreast of new technologies which will begin to color international human expansion into space during the next century.

With increasing emphasis being placed on observing Earth from space with multispectral instruments, more complicated capital-intensive satellites will be placed in GEO. Such satellites will inevitably age or fall victim to advances in technology. While their basic structure may remain viable, their electronic systems and sensors will require upgrading as new technologies emerge. Economic benefits will accrue to that nation or nations with an ability to refurbish, repair, or upgrade such satellites. This requires transportation between GEO and LEO where facilities at space stations of the 21st century can be used to service or upgrade the satellites.

The use of aeroassist to dissipate the energy of return from GEO to enter into LEO is highly desirable from an economic standpoint since it considerably increases the payload-carrying capability of the transportation fleet. An efficient ASTV appears to be the key to commercially viable servicing operations based in LEO.

AFE results will make the design and development of an ASTV fleet practical without such a fleet suffering serious penalties of overdesign of heat shields or the addition of retrorockets to assure orbital transfer. While moving from orbit to orbit beyond LEO requires relatively low-energy expenditures, the transport of materials from the gravitational pit of Earth into LEO is energy-intensive. The less material that has to be transported into space, the smaller will be the fleet of Space Shuttles and expendable launch vehicles needed to initiate or service space operations.

Ultimately, it may be found opportune to establish manned stations in GEO. Again, the use of ASTVs to move personnel back to LEO for return to the Earth's surface via the Space Shuttle Orbiter will require an efficient human-rated ASTV fleet. The basic data gathered by the AFE will be essential for designing any such ASTV.

In the next century it is most probable that the United States will return to the Moon and start to develop that world as a research base and as a source of raw materials. For example, deep-space radio astronomy can best be achieved by radiotelescopes based on the far side of the Moon where they are screened from electromagnetic pollution of Earth's many transmitters (Figure 6-1). A permanent research base on the lunar surface will also ultimately lead to the development of facilities to utilize lunar materials, possibly to support large space stations in orbit around Earth, or to construct interplanetary spacecraft. Moving material from the lunar surface to LEO requires less energy than moving an equivalent amount from the Earth's surface to LEO. In a developing space program beyond LEO, utilizing the resources of the Moon appears very attractive.

Such uses again require an efficient ASTV system to allow the freighters from the Moon to be captured into Earth orbit. This will provide another long-term benefit to the understanding of the basic aerophysics of aeroassist technology, the groundwork for which will be laid by the AFE program. This program is thus an important investment in the technological future of the nation.

Looking farther into the future, it seems inevitable that humans will journey to, land on, and establish a permanent presence on the planet Mars (Figure 6-2). There are many reasons for this which are beyond the scope of this publication, but which are discussed in recent literature including the Report of the National Committee on Space (1987), the Ride report on America's Future in Space (1988), and several Case for Mars study reports over the past 5 years.

Aerobraking and aeroassist technology will be essential for economical missions to Mars. They will be used to increase payload capacity, achieve maneuvers to specific landing locations, return science samples to Earth, and return personnel to Earth. If propellants are used to slow a

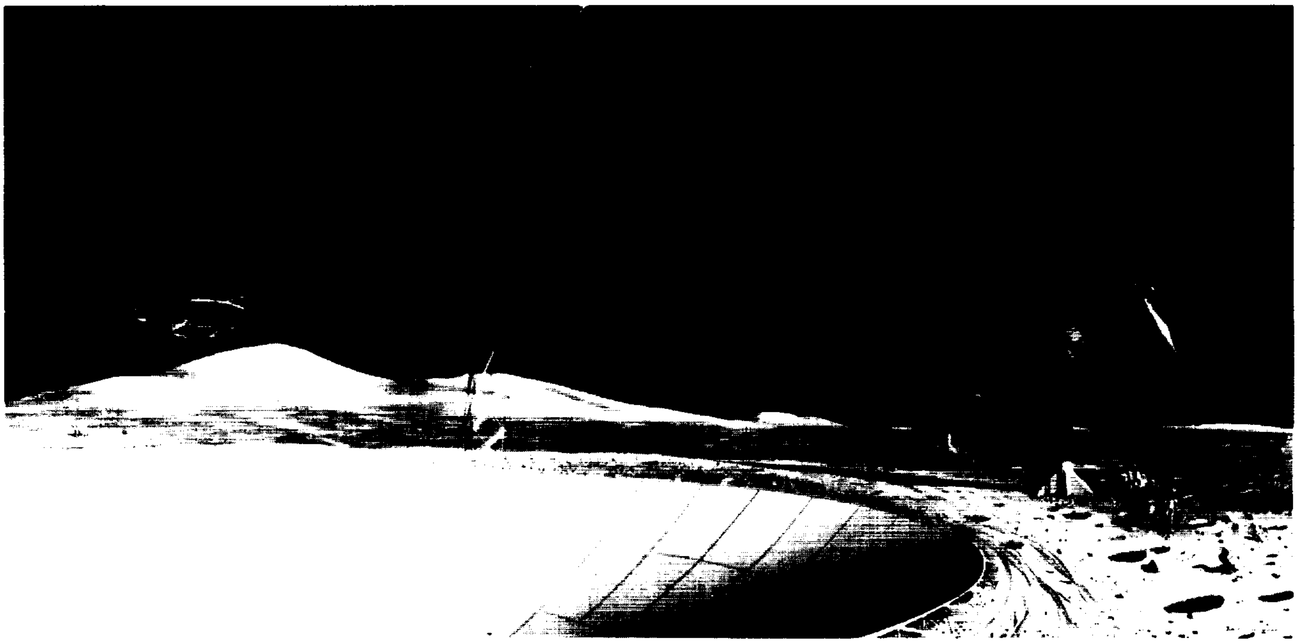

Figure 6-1. Establishment of research stations on the Moon, e.g., a radio astronomy station on the far side of the Moon will be economically possible only if aeroassist vehicles can be used for returning personnel and materials to LEO.

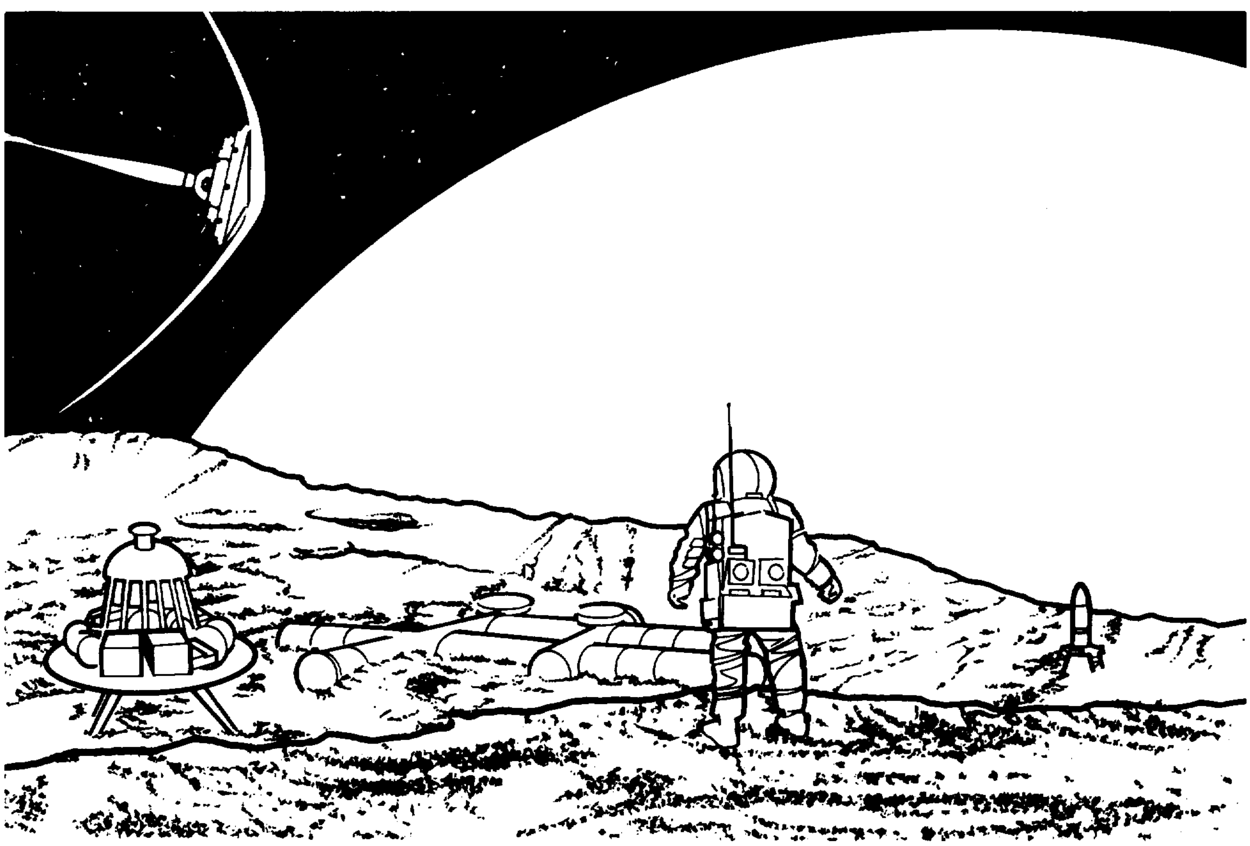

Figure 6-2. This artist's concept of human operations on Mars shows an aeroassist vehicle traveling through the upper atmosphere of the Red Planet. Aeroassist seems essential to making a human presence on Mars economically feasible.

spacecraft for a Mars mission, almost twice as much material has to be lifted from the Earth's surface to LEO. While some of these vehicles will require new technologies beyond those suggested for the ASTVs, they will rely basically on the same fundamental data concerning hypersonic flow and heat transfer under nonequilibrium flow conditions.

Winged gliders with sharp leading edges will be required in missions where high cross ranges are needed, such as landings in high latitudes. Biconic vehicles may be required for transportation of heavy freight, and blunt-nosed aeroassist vehicles will still be used in some scenarios for aerocapture at Mars and Earth. Each of these systems will need to be evaluated by CFD models which, as was mentioned in an earlier section, rely upon accurate data concerning all the parameters involved in hypervelocity flight, validated by flight data.

While the AFE program will provide data for many of these parameters, the wide range of aeroassist environments to be experienced in future space missions (Figure 6-3) require that additional concurrent research should take place using test vehicles with ablators and higher L/D ratios. Such vehicles, carried aloft and recovered by the Space Shuttle, would fly on missions similar to that of AFE vehicle, but at higher speeds of entry into the Earth's atmosphere and at different altitudes. These concurrent tests are needed if the nation is to keep up with and preferably lead in the important space transportation technologies which are capable of yielding great economic benefits to humankind in the 21st century.

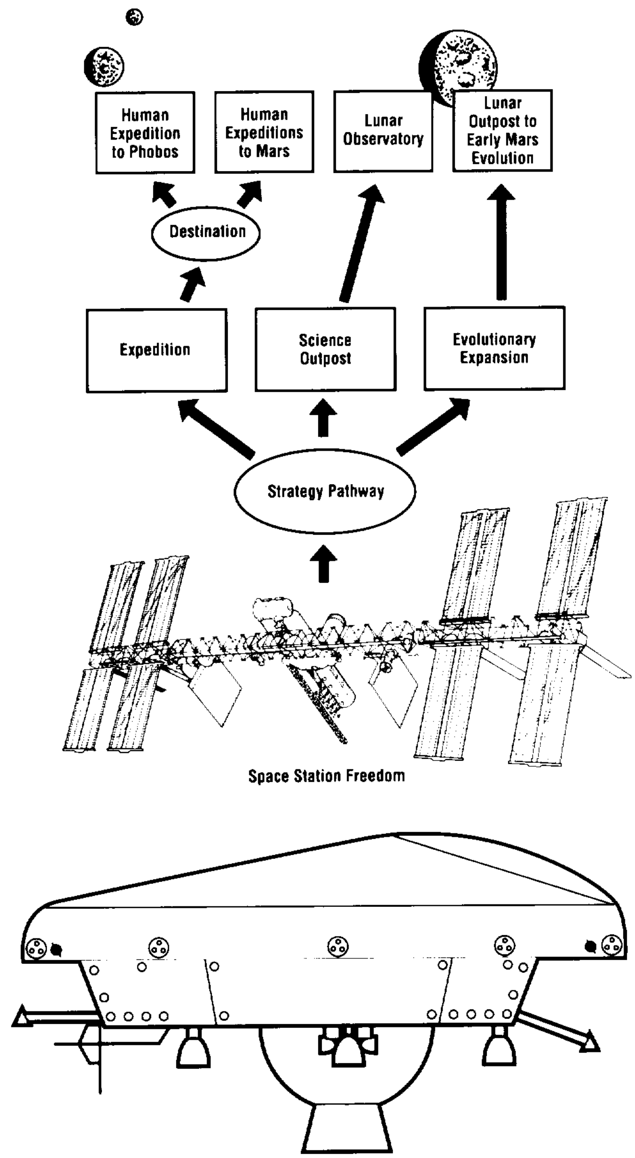

Figure 6-3. Human plans to expand into the Solar System through operations in LEO will be based on the firm foundation of an efficient ASTV system which, in turn, depends strongly on the basic science data to be obtained by the AFE mission.

GLOSSARY

ABLATION: Erosion of material from a heat shield to absorb and transport heat away from a payload, usually by the removal of surface material by sublimation, vaporization, or melting.

AEROASSIST: Use of atmospheric lift and drag to maneuver a spacecraft.

AEROBRAKE: A structure to deflect airflow around a spacecraft and provide aeroassist.

AERODYNAMICS: The science dealing with the motion of air and other gaseous fluids, and of the forces acting upon bodies moving through such fluids.

AERODYNAMIC PARAMETERS: Nondimensional coefficients relating to aerodynamic forces or moments, such as a coefficient of drag or a coefficient of lift.

AEROPASS: Passage of a spacecraft through an atmosphere to utilize lift and drag forces.

AEROTHERMODYNAMICS: The thermodynamics of airflow moving around a body at very high speeds where the thermodynamic properties of the gas become important.

ARC-JET: A device to simulate high-speed airflow by creating an electrical discharge along a narrow channel to heat air or a test gas flowing through that channel.

BALLISTIC PATH: Path of a body moving freely in a gravitational field at less than orbital velocity, and acted upon solely by the gravitational field and the resistance of the medium through which it passes.

BALLISTIC RANGE: A test range in which a gun fires a projectile at high speed along a ballistic trajectory while its flight path and velocity are monitored and recorded.

BASE HEATING: Heating of the rear of a spacecraft.

BOUNDARY LAYER: The layer of air near a surface with an airflow over that surface which is affected primarily by the viscosity of the fluid; the flow may be laminar or turbulent. In aerodynamics the boundary layer is sometimes arbitrarily extended from the surface to a point at which the flow has 99% of the stream velocity.

CATALYSIS: Chemical reaction caused by a substance which itself does not enter into the chemical reaction or is changed by the reaction.

CISLUNAR: Space within the orbit of the Moon.

COMPUTATIONAL FLUID DYNAMICS (CFD): The science of computer simulation of the conditions within and patterns of a flow of fluids.

COMPUTATIONAL MODEL: Model developed through use of CFD to show how a spacecraft is expected to perform under a given set of conditions.

CONVECTIVE HEATING: Transfer of heat by mass motion of a fluid bringing to a surface heat which is transferred to that surface from the fluid.

EQUILIBRIUM: A state within a gas in which reactions between the components are proceeding equally in forward and backward directions so that the relative concentrations of the components would not change with time if so left at the condition.

FLUID DYNAMICS: The dynamics of the flow of gases around bodies immersed in them, such as a spacecraft traveling through an atmosphere.

FLOW FIELD: The region of gaseous flow around a body immersed in an atmosphere and moving relative to that atmosphere.

GAS SPECIES: The various chemical components of a gas.

GEOSYNCHRONOUS EARTH ORBIT (GEO): Strictly an orbit (circular or elliptical) in which a body completes a revolution in the same period that Earth rotates on its axis; more generally applied to a body moving in a geostationary circular orbit in Earth's equatorial plane in which the body remains stationary with respect to an observer on the surface of the Earth.

HEAT SHIELD: A protective device to block the transfer of unwanted heat into a spacecraft.

HIGH EARTH ORBIT (HEO): An orbit around Earth beyond LEO.

LIFTING BRAKE: A spacecraft aerodynamically shaped to provide some lift and much drag to change the path of a spacecraft through an atmosphere.

LOW EARTH ORBIT (LEO): An orbit, usually close to a circle, just beyond the Earth's appreciable atmosphere at a height sufficient to prevent the orbit from decaying rapidly because of normal conditions of atmospheric drag.

NONEQUILIBRIUM: A state within a gas mixture in which reactions have not reached equilibrium. The composition would change with time if left in the condition.

PHENOMENOLOGICAL MODELS: Computational models that describe the phonomena expected under a given set of circumstances.

PLASMA: A state of matter in which molecules and atoms are electrically charged and are not bound to each other chemically, and exist with a population of free electrons.

PLASMA JET: A jet consisting of charged particles to simulate conditions of very-high-speed atmospheric flow.

RADIATIVE HEATING: Transfer of heat by radiation without contact between the hot and the cold media.

RADIOMETER: An instrument to measure amount of radiation.

SHEAR LAYER: A layer along a flow field across which there occurs an abrupt change in velocity of the fluid.

SHOCK LAYER: A layer of fluid between the shock wave and the vehicle in which the velocity of the fluid has changed from supersonic or hypersonic to subsonic velocity.

SHOCK TUBE: A relatively long tube in which brief, high-speed gas flows are produced by the sudden release of high-pressure gas into the tube that produces a traveling shock wave along the tube with high-speed flow behind the shock.

SHOCK WAVE: A surface of discontinuity through which a fluid moving at high speed undergoes a finite decrease in velocity accompanied by an increase in pressure and temperature, or vice versa.

SPECTROMETER: An instrument to measure precisely and categorize radiation at different frequencies.

SUPERCOMPUTER: A modern digital computer possessing extremely high speed of operation, large storage of information, and typically with parallel processing to handle many computations very rapidly.

SURFACE CATALYSIS: Triggering of reactions within a gaseous mixture by the catalytic action of material in a surface in contact with that gaseous mixture.

THERMAL PROTECTION SYSTEM (TPS): A system designed to protect a vehicle such as a spacecraft from undesirable heating by rejecting, absorbing, or radiating unwanted heat.

THERMOCOUPLE: A device that generates an electrical potential by the effect of heat on dissimilar materials so that the temperature can be measured.

VISCOUS EFFECTS: Effects of the property of a fluid to support tangential stresses and resist being deformed.

WAKE REGION: The region of atmospheric flow behind a spacecraft traveling through an atmosphere.